New Ways to Collect Traffic Data, New Challenges for Road Network Authorities

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Nouvelles méthodes de collecte des données de trafic, nouveaux enjeux pour les gestionnaires de voirie

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HECTOR : C'est beau, la Grèce ? [...]
HÉLÈNE : C'est beaucoup de rois et de chèvres éparpillés sur du marbre.
HECTOR : Si les rois sont dorés et les chèvres angora, cela ne doit pas être mal au soleil levant.

— Jean GIRAUDOUX
La Guerre de Troie n'aura pas lieu

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New ways to collect traffic data, new challenges for road network authorities

Luc CHARANSONNEY

Thesis directed by Vincent AGUILÉRA

English Abstract

Road traffic evolves in a context which has undergone three major changes in the past two decades: first, a political change, reshaping the car's role in cities; second, a technical change, through which both vehicles and drivers emit and receive information independently of road authorities' roadside infrastructure; and finally, a financial change, as traffic management infrastructure has heavily relied on public funding which now becomes scarcer.

From the perspective of a key road authority, the City of Paris, the Author, in charge of assessing the impact on traffic flow of major disruptive policies, addresses how "new traffic data" renews the road authority's knowledge of the traffic, on technical grounds.

The Author has worked on Bluetooth travel-time and GPS based Floating Car Data datasets. He believes he makes two major contributions in the field.

He first shows that traffic data and traffic information have always been at the core of the road authority's concerns, deeply related to the available technology, the missions of the road authority, and the theory attempting to bridge the gap between the two.

Through the technical assessment of traffic-related policies (road closures, speed-limit reduction), based on two types of "new traffic data" (GPS speeds and Bluetooth travel-times), the Author analyzes the characteristics of the two datasets, the results they yield and how they complement legacy fixed-sensor based data. They allow the road authority to grasp user-perspective information whereas legacy data mostly offered a collective flow perspective. This, in turn, reshapes the decision-making process of road authorities.

Nouvelles méthodes de collecte des données de trafic, nouveaux enjeux pour les gestionnaires de voirie

Luc Charansonney
Thèse dirigée par Vincent Aguiléra

French Abstract (Résumé en français)

Le trafic routier évolue dans un contexte qui a connu trois changements majeurs ces deux dernières décennies : changement politique tout d'abord, avec la remise en cause de la place jusque-là occupée par la voiture en ville ; changement technologique ensuite, par lequel tant le véhicule que son conducteur produisent et reçoivent des données indépendamment des infrastructures de gestion du gestionnaire ; changement financier enfin, alors que les systèmes de gestion du trafic sont très dépendants de finances publiques de plus en plus contraintes.

Dans ce contexte, l'auteur, du fait de ses fonctions, adopte le point de vue d'un gestionnaire de voirie clé, la Ville de Paris. En charge de l'évaluation des conséquences techniques des politiques de circulation sur l'écoulement du trafic motorisé, il s'intéresse ici à la manière dont les "nouvelles données de trafic" renouvellent la connaissance technique du gestionnaire sur la demande.

Pour ce faire, l'auteur montre d'abord que les données de trafic et l'information trafic ont toujours été au cœur des préoccupations du gestionnaire. Données et information sont profondément liées à la technologie disponible et aux missions mêmes du gestionnaire. Les développements théoriques, alimentés par les données, tentent ainsi de lier les technologies avec les missions du gestionnaire.

Ensuite, à travers l'évaluation technique de politiques de circulation (fermetures de voie, réduction de la vitesse limite) sur la base de deux types de "nouvelles données" (vitesses GPS et temps de parcours Bluetooth), l'auteur analyse les caractéristiques de ces jeux de données, les résultats auxquels ils permettent de parvenir, et la manière dont ils complètent la connaissance tirée des capteurs fixes historiques. Ces "nouveaux" jeux de données permettent au gestionnaire d'obtenir une connaissance de la demande du point de vue des usagers, alors que les capteurs fixes fournissent principalement un point de vue collectif de flux. Cette richesse nouvelle d'information redéfinit les schémas de décision du gestionnaire de voirie.

Acknowledgments

I have plenty of metaphors coming to mind to describe my thesis: an odyssee across the Aegean, a winding mountain road, a foggy lake, a ride on a Paris suburban train at peak time...

Anyway, along my work, I have been accompanied, led, beared by many people.

The first person I'd like to thank here is my beloved Director, Vincent Aguiléra, for all his work and support.

At my workplace, the PCE Lutèce, I would like to thank all the colleagues. I especially thank Michel, Ghislaine and Calixte for easing my professional missions and my thesis: although the two evidently overlapped, they often followed different paths. I thank Gérard for introducing me to traffic management and the subtelties of Parisian traffic engineering. I thank Philippe for providing the required IT material and listening to my thoughts.

I would like to thank all the companies with which I have worked for the traffic data and equipments I based my work on.

At the lab, I thank the many people I've met, discussed with, drank (more or less good) tea with, joked with... The lab board (Pierre, Sophie), the lab administration (Sandrine, Sandrine, Virginie), the Ecole des Ponts library (Delphine), the lab researchers (Alexis, Anne, Cyril, Gaële, Laurent, Laurent, Mariane, Nicolas, Philippe, Virginie, Zoi, ...), my fellow PhD students (Aude, Benoît, Emmanuel, Joséphine, Louis, Mallory, Matthieu, Maylis, Paolo, Vincent...), and my two office mates Xavier and Jaâfar.

I also thank my family and friends; they know who they are.

From an aesthetic perspective, I thank various composers for providing the soundtrack in which this whole work evolved: Claudio Monteverdi, Michelangelo Falvetti, Franz Liszt, Mikis Theodorakis, David Bowie and many others.

At last, I would like to thank myself, for all the great moments we have had and will have together.

Foreword

In the Summer of 2013, I completed my engineering Master of Science degree at the École des Ingénieurs de la Ville de Paris (EIVP). Out of the three years of study, I was able to spend one year at the École Nationale des Ponts et Chaussées (ENPC) to specialize in Transport and Highway Engineering, which are among my lifetime passions.

Afterwards, as a civil servant of the City of Paris, and wanting to keep going inside the field of transportation, I took a then available engineer's position at the Poste Central d'Exploitation Lutèce (PCE Lutèce), the inner Paris Traffic Management Center (TMC), which is in charge of its arterials and traffic lights. My job was to take care of the traffic statistics inside Paris, and investigate new means of collecting and analyzing traffic data, as the legacy loops infrastructure was becoming harder to maintain. Discussions had been engaged with several companies before my arrival. Moreover, there were great political expectations behind these technologies, as traffic statistics played a key role in the political agenda of the City of Paris, which aimed at further limiting motor traffic inside the city by closing off or reducing the capacity of major roads. I had drawn a PhD project related to my upcoming work on the "new" traffic data, which was accepted by my hierarchy and supported by my manager, Michel Le Bars.

Meanwhile, Vincent Aguiléra, who had followed my final internship for my engineering degree, was at the time researcher at the Laboratoire Ville Mobilité Transport, and had been working on these "new" datasets for a few years. He showed great interest to my PhD project.

My PhD report accounts for both the research and operational work I carried out in the last four years, between the Summer of 2013 and the Summer of 2017. My professional environment, namely the PCE Lutèce, offered a great opportunity to put into perspective the "new" traffic data with the dealings of an urban TMC and the heavy political agenda that caused major disruptions to the road network.

This is what you are about to read. I hope you will enjoy reading it as much as I had pleasure investigating, researching, and in the end writing it through the course of these past four years.

Luc Charansonney
August 2013–January 2018, PCE Lutèce, Paris, France.

Introduction

1 Context of the PhD memoir

In recent years, motor traffic, and both its stakeholders (the road authorities, the drivers) and the infrastructure it relies on (the road, the sensors), have undergone three major political, technological and financial changes.

The political change, perhaps the most emblematic of the three in European cities like Paris, is the reshaping of the "car and city" relationship. Political action in cities has since the 1990s veered from car-oriented views to policies favoring "sustainable" modes of transport (public transit, cycling, walking) and re-balancing space use between these different modes, thus reducing the car's footprint on urban road networks.

The technological change spans throughout the 1990s and 2000s: it is the spreading use of GPS location services and mobile Internet connectivity. This quickly had direct consequences on traffic: vehicles themselves have become sensors, and nowadays the knowledge of traffic is transitioning from dedicated, roadside based sensor infrastructures (like traffic loops), managed by public bodies (road authorities) to vehicle-based sensing. The latter has become known as probe vehicle or floating car data, whose collection is managed by the private sector.

Finally, the financial change is the translation of a general recess of public spending in road infrastructures, after decades of massive road building following World War II. The centralized traffic management systems devised and set up in the 1970s-1990s were generally renewed in the 2000s-2010s so they could provide traffic signals preemption to develop segregated surface transit routes (Bus Rapid Transit, BRT, and Light Rail Transit, LRT, lines). Nonetheless, the "legacy" network of sensors they are based on are costly and complicated to maintain, and are now gradually being decommissioned in favor of vehicle-based sensing or of cheaper devices making use of these technologies. New roadside sensors are called for, like for V2X communication, but the question of funding the installation and maintenance of such devices remain yet to be solved.

2 The Paris region and the author's position

The Paris region, at the center of which lies the City of Paris, is a key example of a complex world metropolis with dramatic congestion on both its mass transit and road networks. This is potentially a daily demand of millions people over a supply whose responsibility is split between different overlapping public and private bodies.

Within the City of Paris, the road authority role is played by the Direction de la Voirie et des Déplacements (DVD), literally the "Roads and journeys administration".

Within the DVD, the PCE Lutèce, officially known as Section études et exploitation (SEE), is in charge of controlling projects and operating assets related to traffic. Traffic is understood as all the modes that travel on the road network, even though the original traffic management system was mainly aimed at private car traffic.

Through the course of his doctoral thesis, the author worked as an engineer at the PCE Lutèce. His operational role, on which his doctoral thesis relies, was to investigate and assess the “new traffic data” provided by the rising traffic information intermediaries, and provide an operational framework for statistical use of these datasets.

The resulting 2013-2018 five years of work involved working with GPS-based Floating Car Data and Bluetooth-based travel-times, from exploring the datasets to delivering technical assessments of traffic conditions using these datasets. This does not deal with the political aspect of traffic policies assessment, which was out of the author's scope both as an engineer and a PhD student.

The scope of this doctoral dissertation does not cover the economical aspects of the traffic information market. It also does not cover the political issues behind traffic-related policies. Its purpose is not to develop a “data-fusion” model that would mix several data sources to model traffic. The author places his work “upstream” of these issues.

3 Questioning

The author, in his doctoral dissertation, addresses the following issue: **from the perspective of a road authority, what are the metrological and organizational changes induced by the technological shift triggered by the new methods of travel-time measurement?**

The author believes his thesis contributes to a better understanding of the “new traffic data”, namely the Bluetooth travel-time and GPS based Floating Car Data datasets he has worked during the course of his work.

Based on a selection of key studies found within the traffic-related literature (mainly from the 1920s to the 1960s), he shows that the novelty of these datasets is in fact deeply linked to the questions traffic engineers and road authorities have been struggling with since the rise of motor traffic. The variables that can now be directly and cheaply measured or estimated by the new technologies have been sought for since the beginning of traffic engineering: travel-time (and its reciprocal, the “space-mean” or “flow” speed) estimation both through space and time. These variables complement the well-known legacy variables (flow, concentration, spot speed) of traffic engineering.

The second major contribution the author believes to have made is on the main properties and uses of these new datasets, from the perspective of a road authority that needs to assess traffic-related policies in the context introduced above. His work thoroughly describes the datasets at stake, and shows examples of their use through real-case operational studies (closure of a tunnel under one of Paris main traffic hubs, closure of a major crosstown expressway, lowered speed limits).

The dissertation is therefore organized as follows.

An introductory chapter, Chapter 1, Paris and its Traffic, sets the general context on traffic viewed as a supply and demand interaction, and on the role played by traffic information and data. It also presents the Paris case, the organization of the City of Paris as a traffic authority, and the author's position in the structure.

The dissertation is then split in two: Part I, Traffic data and traffic information: linking the Traffic Management Center and the driver, and Part II, “New” traffic data: expanded ways to assess traffic.

Part I, Traffic data and traffic information: linking the Traffic Management Center and the driver, thus addresses the following issues:

1. How has traffic data answered the operational needs of the road authorities, and allowed the inception of both traffic engineering and of the Traffic Management Centers most urban road network are today headed by? Should "new" traffic data really be opposed to "legacy" traffic data?
2. What have the successive technical advances of the traffic data collection and traffic information broadcasting, from the 1920s to the 2010s, meant for the Traffic Management Centers' relationship with the drivers? How is that relationship challenged by today's widespread use and collection of crowdsourced traffic data?

Within this Part, Chapter 2, The "new" against the "old"? The quantification of traffic, addresses the first of the above issues: How has traffic data answered the operational needs of the road authorities, and allowed the inception of both traffic engineering and of the Traffic Management Structures most urban road network are headed by? Should "new" traffic data really be opposed to "legacy" traffic data?

Chapter 3, The evolving relationship between drivers and road authorities: occasional, centralized, then shared. Paris and Lyon cases, from the 1920s onward, addresses the second of the aforementioned issues: What have the successive technical advances of the traffic data collection and traffic information broadcasting, from the 1920s to the 2010s, meant for the Traffic Management Centers' relationship for the drivers? How is that relationship challenged by today's widespread use and collection of crowdsourced traffic data?

Following Part I, Part II, "New" traffic data: expanded ways to assess traffic, addresses the following issues:

1. What data can the Traffic Management Center "catch" outside of its legacy sensors infrastructure?
2. What are the operational traffic indicators these "new" traffic data provide? What operational purposes can they serve for the Traffic Management Center?

Within this Part, Chapter 4, Place de l'Etoile: First encounter with Bluetooth beacons, followed by Chapter 5, Voie Express Rive Droite: Bluetooth beacons for a major road closure, focus on the travel-time indicator, as collected through Bluetooth travel-time technology to assess two major, disruptive traffic-impeding decisions. The first, in 2015, is the closure of an underpass under one of Paris major intersections, the Place de l'Etoile. The second, in 2016, is the closure of a major cross-city expressway. In both cases, the purpose was to assess Bluetooth travel-time usefulness in keeping track of travel-times before and after disruptive measures, along with providing the City with a quantification of the disruptions.

Chapter 6, GPS speed FCD: the story of two different providers, then focuses on GPS-based FCD speed data, and the difficulties met in using the data. It shows that, even though not relying on authority's ground equipments, this "new" dataset is not, as already shown by Bluetooth, straightforward or "plug-and-play".

Chapter 7, GPS speed FCD: assessing speed-related policies, focuses on a major speed-related issue: assessing the lowering of speed limit in Paris, with two cases. The first case is the lowering from 80 to 70 km.h^{-1} of the speed limit on the ringway, and the second is the establishment of 30 km.h^{-1} zones. GPS-based FCD allows the collection of instantaneous speeds of vehicles throughout the network.

Part II is followed by the Conclusion of the dissertation.

Chapter 1

Paris and its Traffic

1.1 Traffic: a supply and demand interaction

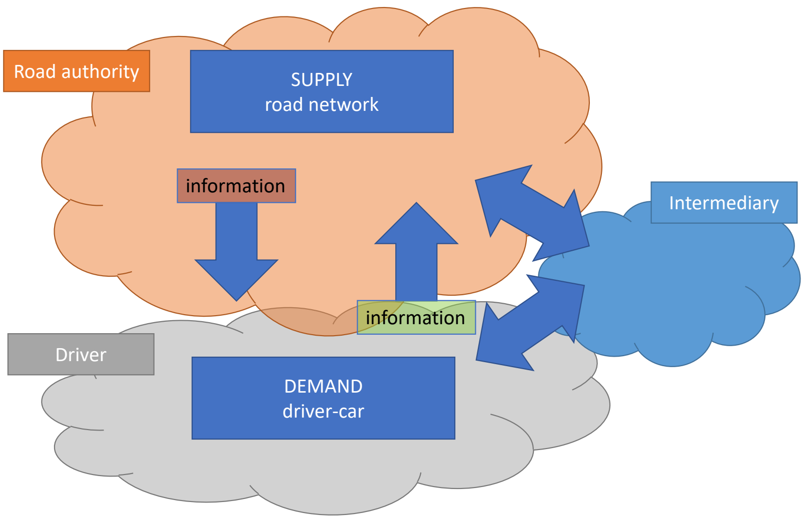

Figure 1.1 – Supply and demand view of traffic, along with the information intermediary.

Traffic can be described as the interaction of three elements: the driver, the vehicle, and the infrastructure (the road). From a supply and demand perspective, the driver-vehicle pair can be considered the demand and the infrastructure the supply. In other words, road users make up the demand, and the road, the supply. Traffic then results from the interacting supply and demand.

The traffic situation can either be on the side of the supply or of the demand. The supply is physically finite, as it cannot allow through more demand than it was designed for: it has a capacity. When the demand remains below the supply's capacity, the traffic situation remains satisfying: the supply accepts the whole demand. This state is called free-flowing state. When the demand exceeds the supply's capacity, the supply only delivers an unsatisfying, rapidly worsening answer: the more the demand exceeds the capacity, the less the supply can deliver. This state is the congested state.

Two main categories of stakeholders stand behind the supply-demand view.

1.1.1 The supply

The supply is the road, defined by Article 1 of the 1968 Vienna Convention as "the entire surface of any way or street open to public traffic" ([1]). A road can then be broken down into "carriageways" and "lanes". A "carriageway" designates the "part of a road normally used by vehicular traffic". A "lane" then is "any one of the longitudinal strips into which the carriageway is divisible [...], which is divisible for one moving line of motor vehicles other than motor cycles". An intersection is where two or more roads meet. The set of roads makes up the road network.

The supply is not homogeneous: there are different types of roads, from local streets to main arterials to expressways and motorways. These types introduce a hierarchy in the network. The fundamental distinction lies between all-purpose roads and motorways. The motorway is explicitly defined in the aforementionned Article 1 of the Vienna Convention, as a "road specially designed and built for motor traffic, which does not serve properties bordering on it": its accesses are controlled by the means of grade-separated interchanges. The type of a road is generally related to the quantity of demand it can cater for (its capacity) and the maximum speed it allows the demand to travel at under free-flowing conditions.

There is one main stakeholder behind the supply: the road or highway authority. The road authority is the body in charge of the road network. Its role can be generically defined into three overlapping missions. In French it is known as the "gestionnaire de voirie", litterally the "road manager".

Its first mission, the most crucial, is ensuring the safety of the various users of its roads. Safety is a wide topic that goes beyond the scope of this work. It involves the safety of the road, safety between the users and the road, safety between the users themselves, either within the same category (a car and a car) or between two categories, one usually being considered more vulnerable than the other (the car driver is generally on top of the list as the least vulnerable, the pedestrian being the more vulnerable).

Its second mission is handling the demand. This is a daily, 24-hour, seven-day-a-week task. It involves delivering the best supply to the demand. "Best" covers a variety of meanings. It is seeking the adequacy between the road type and the demand: local traffic vs. through traffic. It is maintaining the infrastructure to provide users with the safest infrastructure with the maximum capacity most of the time. It is controlling the demand, enforcing the policies voted by the political authorities: road-capacity allocation favoring specific categories (mass transit, bicycles, car-sharing, etc.), routing the demand on main roads, sparing neighborhoods' streets from through traffic. Within these lines, the road authority aims at maximising the use of the available supply while minimizing the overall time spent by the demand on the network. This mission is often designated as "traffic management".

Its third mission is on a longer term than the two others: it involves planning, designing and implementing the layouts that serve the policies to be enforced. This spans from building a new road, to reallocating road-space, to closing a road.

Of course, the road network is attached to the territory it serves. Extra-urban issues are by far different from urban ones. Here the author focuses on the urban situation.

1.1.2 The demand

The driver-vehicle unit stands behind the demand.

A vehicle can be of various types: Article 1 of the 1968 Vienna Convention defines several types, reflecting the diversity of uses on the road: "cycle", "moped", "motor cycle", "power-driven vehicle", "motor vehicle", "trailer". The driver is himself defined as "any person who drives a motor vehicle or other vehicle". The driver-vehicle unit such designates very varied situations.

Each individual driver travels from an origin, which he leaves at departure time, to a destination, which he reaches at an arrival time which may differ from his original expected arrival time. His travel, or journey, links an origin-destination pair over a route, traveled in a travel-time. The route is the series of roads he used (the supply), and the travel-time is the time difference between his departure and arrival times. Of course, origins and destinations may be shared by a great number of drivers: that's especially the case when residential and work areas are concentrated at specific locations. This is also true for the supply: individual routes linking shared origins and/or destinations also share common sections of road. The aggregation of individual routes on the same infrastructure makes up the traffic flow.

Thus, there are two scales at which to consider the demand: the individual driver, or the collective flow, an aggregate of individual trips.

1.1.3 Information, in between supply and demand

Supply and demand as described above are in deep interaction. Theoretically, information has to be exchanged two ways and continuously between supply and demand. Technological progress have played a key role since the beginnings of motor traffic in building and transmitting the information between the two sides.

1.1.3.1 Information, from demand to supply

The information from demand to supply has historically been the major movement. In fact, the road authority's three main missions require it to gather a quantitative and qualitative knowledge of traffic, both in the short term (real-time) and in the long term (historical data, statistics). The authority wants to ensure the demand's safety at all times, thus to know the state of its supply (available capacity, incidents) and to act on the demand accordingly.

This brings about two possible scales of study for the demand and of the traffic it generates.

The individual perspective gives the authority a thorough knowledge of origin-destinations. The downside is that historically, gathering such data was impeded by available technologies, and requires considerable manpower. Such studies therefore were rather exhaustive but on a limited perimeter, or with a small fraction of drivers but over a larger perimeter.

The collective perspective, in terms of volume and local speed, is derived from the observation at fixed roadside spots of the flow of traffic. This allows an easy automation of data collection, requiring less manpower than individual observation enquiries

The knowledge of the road authority of the demand over its network results from a trade-off between these two scales of observation. Indicators, mainly volumes (traffic counts at given points, then projected over a road section), road section travel-times (travel-time over a section of road), flow routes (significant aggregation of individual routes) ended up characterizing the demand for the road authority. Through time, these indicators rely both on the data collected during the manned or automated sensor-based observation of traffic, and on theory (reasonable assumptions, models) that generally attempts to bridge the gap between the wanted indicators and the available observation techniques and the variables yielded by the observations. This is typically the case for travel-time, which could hardly be measured in real-time over a whole network, and ended up being estimated from direct measurements on small samples, combined with models based on spot automated measurements of traffic.

1.1.3.2 Information, from supply to demand

The information delivered by the supply to the demand is funded on two aspects: the authority's missions and the idea the authority holds of the supply, derived from the information it retrieves from it.

Information from the supply to the demand is both static and dynamic. The traffic signs communicate to the driver the regulations and routes enforced by the road authority. The radio is the historical medium allowing the transmission of dynamic information from the supply to the demand. It allows to act on the demand by informing it of the whereabouts of the supply (mainly, congestion issues, either caused by demand overwhelming the nominal capacity of the infrastructure, or by an incident reducing the nominal capacity). Variable Message Signs are a second tool to inform the demand, and are directly managed by the road authority. In both cases, these mediums inform the driver "in general", as part of a flow. The most-individualized it gets is by informing the drivers traveling on the same route and to or through the same destination, like a district or an interchange.

Gradually, drivers have come to expect both reliable and invidualized information from the authority. The major technological shift happened during 1990s: onboard devices gradually meant that individualized demand-based information collection was now possible (now known as crowdsourcing), subsequently improving the preexisting supply-driven information collection (mainly done through roadside observation). This shift means that the mass collection of individualized demand data now becomes possible. The second consequence is that the authority looses its monopoly on the demand-supply link: a third actor, the private sector, comes into play and can therefore follow its own strategy.

1.1.3.3 Traffic data, traffic information

Information is at the node between supply and demand: it is through it that they get to know each other.

Information must not be confused with data. Information relies on data. As both are about the supply-demand interaction, i.e. the traffic, they are usually referred to as respectively traffic information and traffic data.

Traffic data qualifies or quantifies traffic on a road. The qualification of traffic essentially refers to its state (congested, free-flowing) and events that may affect it (accidents, construction works, etc.). The quantification refers to the variables associated with the traffic: count, flow, speed, occupancy, etc.

In 2017, traffic data comes from a variety of sources, from road sensors to the vehicles or drivers themselves, and is the result of complex decision-making processes, driven by the many parties involved.

Traffic data has been important from the start of motor traffic issues in the early XXth century. It grew in importance with the rise of massive traffic data collection systems in the 1950s-1990s period, along with the creation of a traffic-dedicated structure sitting under the traffic authority: the Traffic Management Center (TMC) [2, 3], also called Traffic Control Center, Traffic Control Unit, etc. Centralizing information coming from the network, the TMC holds a comprehensive view of it and aims at controling it, hence its name. Traffic operators can follow traffic management operations in response to traffic demand and available infrastructure supply, the supply being altered by various phenomena, like the weather, roadworks or incidents.

Traffic information is an end-product of traffic data, and is itself a data aimed at either the supply or the demand. It informs it on traffic and road conditions. It makes traffic data intelligible to the receiving party, helping him in fulfilling his task (like, for a road user, completing his journey). The expectations of the receiving parties have evolved through time, thanks to the technological, political, environmental, economic factors.

Both the supply and demand exchange information, referred to as traffic information, that relies on data, referred to as traffic data. Each side has expectations, and each side holds an opinion of what the other side should expect and do: the road authority wants to get the broadest understanding of the demand so that it can control it, minimize the overall delay and provide it with the best supply possible both in the short and longer term. It seeks what could be called an "collective or network optimum". The user wants an individualized, reliable information for his journey, minimize his delay, and get on time to his destination. He seeks what could be called an "individual optimum".

The data and information that feeds the exchanges between the two aforementioned stakeholders is not necessarily entirely managed by them. There are intermediaries in between. These intermediaries have historically been occupying the supply to demand information channel, and been highly dependent on the road authority for data. This dependence was caused by both the great centralization of traffic control, supported by important public funding levels, and the associated technical limitations that made roadside based observations the most affordable and easiest way of obtaining network-scale data on traffic. An example of such intermediaries would be the private radio stations, who counted on thorough traffic information flashes to grow their audience. Starting in the late 1980s, the floating sensors revolution occurred, at first through navigation-dedicated onboard units, later supplemented by devices that not only stick to the vehicle, but also to the user, the smartphone being the flagship of this latter type of devices. This means network-wide, cheap traffic data and information, emanating from the vehicle, with most costs covered by the users. The providers of such equipments and associated services became new stakeholders, drawing data not only from the supply, but also from the demand. That knowledge then allows to know the demand and be able to somehow control it, without necessarily being associated with the road authorities. These intermediaries thus become a third category of traffic stakeholders: the commercial stakeholders, whose business is to collect and sell demand data and route the demand.

Questions naturally arise from these general thoughts: how are is the relationship between demand and supply, between the road authority and the road users, reshaped? How do the new intermediaries interact, or interfere, with the demand and the supply? How can a road authority enforce a policy decided by an elected government, while at the same time part of the control of the demand gets out of reach? Do the road users have anything to gain from the rising complexity associated with having more stakeholders? Who assumes the cost of running the services? Who regulates them?

From these stakeholders' issues arise a mirrored questioning at the traffic data level. It resides within the mandatory distinction between two aspects of the traffic data, the first being the measurement of the physical phenomenon of traffic, the second the interpretation made of it by the various stakeholders, namely the driver, the traffic authority, the political arena, the commercial stakeholders.

The first aspect is the traffic data as the measurement of the physical phenomenon of traffic. The image it gives of traffic is related to the sensor itself (Eulerian or Lagrangian) and to the supply-and-demand interaction within its range of observation. This can be called the "traffic ground truth".

In order to fulfill its missions, the road authority carries out a technical interpretation of the physical measurement. This level of interpretation is the closest to the empirical ground truth, and is often associated with direct observation and field knowledge. This both validates the data collected, but also changes it into reliable information: along with the traffic variables, events are drawn. The road's authority interpretation is thus very closely related to the traffic ground truth.

The other stakeholders, the driver, the commercial and the political, hold a more self-driven interpretation.

The driver holds its own interpretation of traffic. It can be considered a mix of his experience, from the origin-destination pair he travels the most (around his home or his workplace), to the locations he seldom visits. His vision is also influenced by the information he receives from other stakeholders.

The political interpretation of traffic data fuels the political decision making process that will feed policies the road authority will in turn have to enforce. The political decision will nonetheless very often override the traffic ground truth, and data will be interpreted as to serve the decision.

The commercial interpretation is an in-between between the driver, the road authority, the politicians. A key issue for commercial solutions is to be essential to drivers. The driver is a customer. This is based on several factors. The first factor is to communicate on a worsening trend of traffic conditions, while presenting the commercial solution as the way to diminish the consequences on the customer's journey. The second factor is to present the provided information as reliable and time saving.

Traffic results from the interaction between a supply and a demand. Several stakeholders stand behind this interaction. The two major ones are the road authority, standing behind the supply, and the driver, standing behind the demand. In-between, information travels, based on data. This allows each stakeholder to carry out its missions: for the road authority, providing a safe and appropriate supply, for the driver, completing his journey while suffering the minimum delay. The way data, and thus information, is collected is deeply linked with the technological means allowing it. Therefore, the technological evolutions of the past decades, switching the collection devices from the infrastructure to the vehicles, has allowed a third category of stakeholders to emerge, focused on information.

It is necessary to separate the absolute ground truth of traffic, i.e. the traffic data itself and the interpretation carried out by the road authority, from the interpretations derived by the other stakeholders, which are more self-interest driven.

1.2 The Paris region case

This is the global picture in which the Greater Paris area case evolves. It is a key example of a complex world metropolis with dramatic congestion on both its mass transit and road networks. This is potentially a daily demand of millions people over a supply whose responsibility is split between different overlapping public and private bodies.

1.2.1 The administrative status of the City of Paris and its region

The City of Paris is at the core of a region, Île-de-France, also known as Paris region, which houses over 12 million people and 5.6 million jobs spread over 12 000 km^2 [5][1]. The region is split into eight Départements. Paris is at the center, surrounded by two concentric rings of

[1] The statistical figures for surface, population and jobs all come from the INSEE (Institut national de la statistique et des études économiques) database [5].

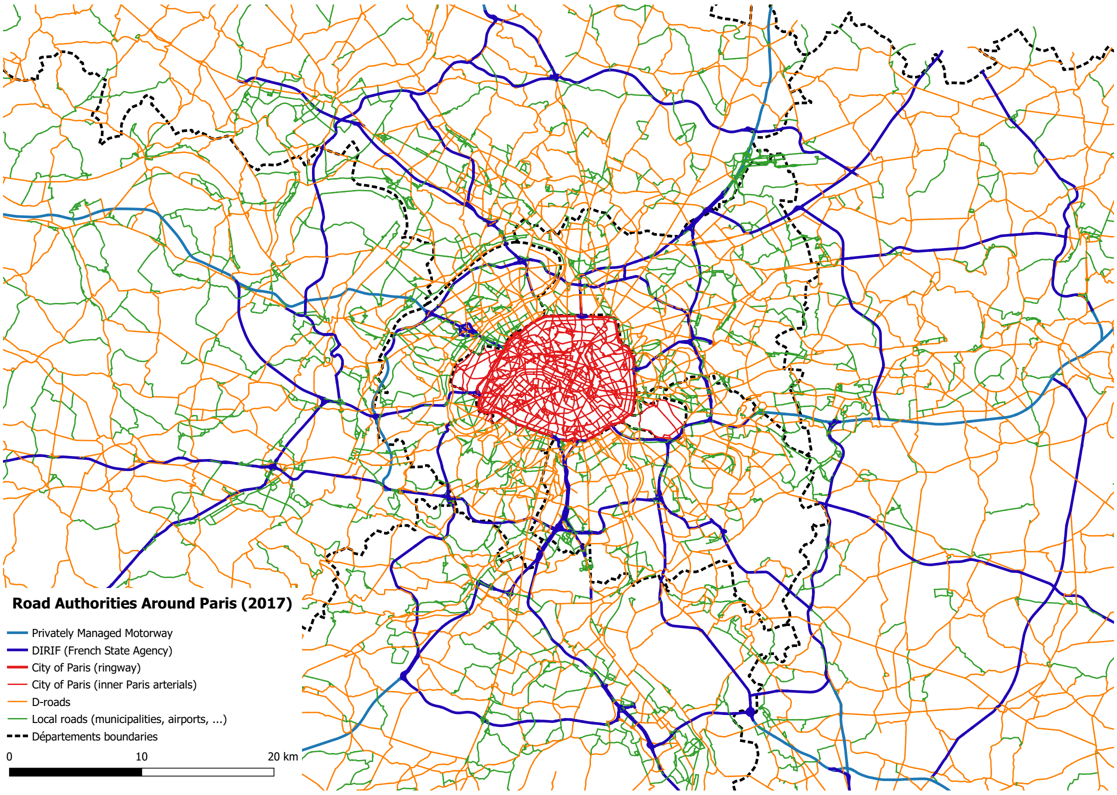

Figure 1.2 – Road authorities around Paris (2017) ([4] with author's post-processing).

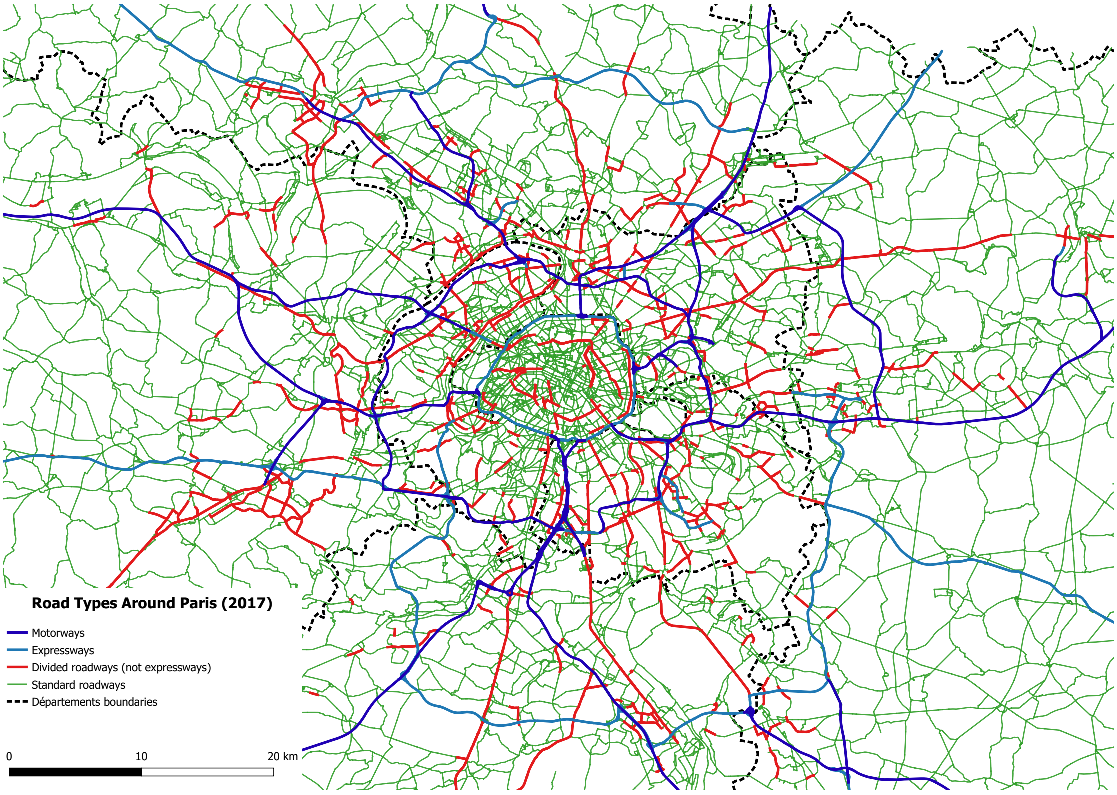

Figure 1.3 – Road types around Paris (2017). The distinction is made between motorways, expressways, standard divided roadways (roads or streets which are not entirely grade-separated and have local accesses), standard roadways (roads or streets that do not fall in the three previous categories) ([4] with author's post-processing).

Départements, an inner ring of Départements neighboring Paris (known as the Petite Couronne, literally "small ring") and an outer ringer (known as the Grande Couronne, "great ring"). Each Département is itself organized into municipalities. The City of Paris and the municipalities of the Petite Couronne are also part, since 2016, of Grand Paris, Greater Paris, although this administrative structure has no authority on transport as of 2017. The City and the Petite Couronne concentrate over half the region's population (more than 6.7 million) and jobs (more than 3.8 million) over 760 km^2. The City itself is an even smaller territory, at 105 km^2 with a population of more than 2.2 million and 1.8 million jobs. These figures easily show the pressure this puts on transportation networks.

Being the capital of France, and owing to its troubled history in the XIXth century, the City of Paris status is peculiar among French municipalities. The history of Paris government can be found in [6]. Up until 2017, Paris used to be both a municipality and a Département, and its elected body, the Conseil de Paris (Council of Paris), acted as the council for both structures. In 2017, the two entities were merged and the City of Paris became a municipality.

The French State always deeply interfered with the City of Paris administration. The Préfet, named by the national government, and whose role is basically to represent the State in each Département and enforce the Law, was from 1800 to 1977 the unelected head of the City's administration. After only two small time lapses in the XIXth century, Paris could finally elect its mayor in 1977.

Unlike other French cities, the Police forces in Paris depend from the Préfet de Police (distinct from the Préfet), i.e. the French State, since 1800. Nonetheless, in the past few years, some fields have been transferred to conventional municipal police. After the first elected mayor took office in 1977, the Préfet de Police retained major responsibilities, most notably, as far as traffic is concerned, the Police forces. In the 2010s, major reforms have watered down the Préfet's role and handed more responsibilities over to the Council of Paris and the Mayor. Nonetheless, many matters remain shared by both the Préfet and the Mayor.

These complex layers of administrative bodies directly translate into a great diversity in road authorities. The massive post-war road building program was mostly directed by the State. This program spanned from the 1950s to 1990s. Then, the devolution process (known as décentralisation in French), increased the local authorities powers and resulted in a greater road authorities fragmentation.

1.2.2 The development of the road network infrastructure (1930s-1970s)

The growth of the region, and of its urban core centered on Paris, throughout the XXth century, was at first accompanied by an extensive streetcar network, which was supplemented, from the 1930s onward (with a hiatus from 1939 to the early 1950s), by private motoring. Rail continued to play role, but concentrated on the mainline radials and on the subway. The growth of motor traffic yielded car-dedicated infrastructure projects in the 1930s, with construction and extensive planning really picking up in the 1950s. The plan was to provide the region with radial motorways branching off an inner ringway circling Paris, and connecting successive concentric outer ringways. Motorway spurs were to cross the City of Paris and various already densely urbanized areas. By the oil crisis of 1973, most radial motorways were completed, along with the innermost ringway (Paris ringway, namely the Boulevard Périphérique) and significant sections of the two outer ones, although with altered plans.

After 1973, the radial motorways that had not been built were axed, as well as most urban spurs that were suffering intensifying opposition. The infrastructure policy then focused on completing the two outer ringways (the second ringway, A-86, and the third ringway, A-104) and treating bottlenecks (bypasses, interchanges, widening), a work which has been going on until nowadays. While the motorway and expressway network was being built, major arterials underwent heavy upgrades, mainly through their widening and the grade-separation of major intersections.

1.2.3 The administrative landscape in charge of the road network

The general rule is that municipalities are the road authority for the local streets (C-roads or unnumbered roads). The arterial network, designating major roads with at-grade intersections and direct local access is shared between the Départements (D-roads) and the State (N-roads). These roads used to be jointly managed by the State, namely by the Direction départemental de l'équipement, Département-based agencies created in 1967 which were widely known as DDE. The devolution process meant the end of these agencies, the N-roads being managed by the State, and the D-roads by the Départements, under independent structures.

The expressway network (voie express), i.e. grade-separated roads with no direct access, is also shared between these two administrations (N- and D-roads).

The motorway network (autoroute) is shared between the State Department of Transportation (A-roads) and private companies for privately-operated motorways.

Successive decentralization movements have transferred most of the arterial network from the State to the Département. The two biggest nationwide waves of downgrading N-roads to D-roads occurred in 1973 and in 2006. Paris region was much more impacted by the 2006 move, when most N-road arterials became D-roads.

The City of Paris does not follow the traditional A-N-D-C-roads schema. Instead, the City of Paris is the road authority for all roads over its territory. Additionally, the Préfecture de Police oversees part of the arterial network and the ringway[2]. Therefore, on this subnetwork, the road authority is shared between the City of Paris (maintenance, planning, management) and the Préfecture (planning, management). Nonetheless, unlike other French municipalities, driving laws enforcement is still a Préfecture's competence over the whole network.

There are therefore six major road authorities for the core Greater Paris area ("Petite Couronne", roughly inside the A-86 orbital motorway):

- the State Department of Transportation, for the A and N-roads;
- the City of Paris, for its network, including the ringway;
- the Conseil Départemental des Hauts-de-Seine, for the Hauts-de-Seine Département;
- the Conseil Départemental de Seine-Saint-Denis, for the Seine-Saint-Denis Département D-roads;
- the Conseil Départemental du Val-de-Marne, for the Val-de-Marne Département D-roads;
- Cofiroute, for the tolled West segment of the A86-motorway ring, built and operated under private management.

1.2.4 The inception and current state of traffic management in Paris region

In line with the previous description of traffic as the result of interaction supply and demand, and with the administrative background of Paris region in mind, this section describes the inception of centralized traffic management for the various road authorities.

[2]The arterials managed by the Préfecture mainly include, since the 2017 reform, those that serve key State and diplomatic facilities.

Major arterials and expressways[3] alike, by the traffic volume they support, have concentrated many of the issues faced by road authorities. The authorities gradually felt the need for centralizing information collection across their networks, as the technology allowed it.

In 1971, the French State issued an instruction that made traffic plans mandatory for cities and urban areas of over 20,000 people [7]. During the 1972-1983 period, the Paris region's main arterials and expressway network became known as the Réseau Régional Contrôlé (RRC), the Controlled Regional Network, with several aims: improving the flow of traffic, improving surface transit performances, regulating parking, and protecting two-wheelers and pedestrians.

This plan funded ground assets for Paris, the Petite Couronne and the Grande Couronne: new road layouts, but also traffic equipment such as traffic lights coordination. The network did not extend into Paris however, only including the ringway and the outermost circular boulevards, known as the Maréchaux.

In this context, the inception of traffic management centers also stemmed from the need to put workforces needed in dedicated locations to increase their efficiency, but also from the technological availability of assets that would allow a centralized supervision from a control room, reproducing power industry practices.

Therefore, the centralized systems came to rely on dedicated telecommunication networks linking the central computer housed in the TMC with ground assets that allow automatic or manned supervision of traffic.

1.2.4.1 Paris Region State expressways

Outside the City of Paris, the State is the road authority for the motorway and expressway network (motorway radials, the A-86 second ringway and the A-104/N-104 third ringway)[4]. The corresponding State body is the Direction des Routes d'Île-de-France (DIRIF), Roads Department of Île-de-France.

In the late 1980s, the State developed a dedicated traffic management infrastructure to manage this network, supervised by its TMC and its underlying system named SIRIUS, Système d'information pour un réseau intelligible aux usagers, "Information system for an intelligible network to its users". SIRIUS went live in 1993 as a system dedicated to the TMC operators to help them with their traffic management tasks over the network, by providing them a centralized, dynamic overview of the network. It had three fundamental functions, oriented toward the needs of the TMC:

- Give at all time the traffic conditions over the network;
- Inform users reliably, precisely and at all time on their journey conditions;
- Alert users in case of a dangerous event (congestion, accident, roadworks)

It mainly relied on fixed road traffic sensors, mostly loops, which gradually equipped most of the State expressway network. The general rule was to implement one sensor per lane every 500 m. Complementary video cameras were installed at strategic locations.

The system also allowed the TMC to communicate with the road users through Variable Message signs, through which events could be signaled to them. A new generation of the system, SIRIUS2, was implemented in 2001-2005, to include automatic incident detection (especially for the tunnel, which hold specific safety regulations) and travel-time computation. User-oriented functions were added to its original operator functions inherited from the original system:

[3] For conciseness and clarity, expressway will be used to generically designate all expressway-like roads, including motorways (autoroutes), except when the distinction between these two classes of road is relevant to be drawn.

[4] Some sections of expressways are D-roads, but they mostly act as spurs to the State network or are isolated bypasses, and have a D-road status because they were funded by a Département.

- Users' safety: detecting and signaling incidents and congestion, signaling roadworks;
- Traffic management: ramp metering, users' recommendations (detours, etc.);
- Users' information: travel-times, projected traffic information, regulations in place.

Communication to the user heavily relies on VMS, along with FM radio flashes.

1.2.4.2 Paris region arterials

Paris region arterials are mostly radial roads stemming from Paris ringway interchanges and a direct continuation of the City of Paris arterials. Their geometry generally includes two to three traffic lanes per way, with at-grade signalized junctions, some fitted with through-traffic overpasses or underpasses. Since the 1990s, surface transit projects, such as light rail or bus lanes, have reduced the general traffic lanes and even involved the removal of many of the grade-separating structures.

Most of these arterials used to be N-roads, and were gradually downgraded (especially in 2006) to D-roads, their authority in charge switching from the State to the Département.

In the line of the 1971-1972 traffic plan schemes, all Départements gradually had at least a few people dedicated to traffic management.

The "lowest level" of traffic management was the synchronization of traffic lights along main arterials, with a ground calculator in charge of traffic lights synchronization, and no associated TMC.

In the Petite Couronne, TMCs were set up by the Val-de-Marne and Seine-Saint-Denis by 1984-1985, following the RRC's goals, to supervise and centralize traffic lights management. The Hauts-de-Seine followed a few years later. These three TMCs, under the authority of their respective Départements, are today in charge of D-roads arterials whose junctions are wired to the corresponding road authority's TMC, with various degrees of spatial coverage in each Département. They also manage traffic light preemption for surface transit.

1.2.4.3 The City of Paris network

The first centralized traffic control units were developed in the City of Paris in the late 1940s and were dedicated to traffic lights synchronization. Several of these units were implemented throughout the 1950s and 1960s, each linked to a pool of signals. The completion of the ringway in 1973 led the Préfecture to consider the City's road network as two categories.

On one side, the ringway, with its motorway-like characteristics, needed specific procedures for its maintenance and management, and a centralized system to oversee the entire road: the Poste Central d'Exploitation Berlier (PCE Berlier, or Berlier TMC) was born. The underlying system went live in the 1980s. The system's algorithms rely on fixed road traffic sensors measuring traffic flow variables (flow, occupancy, speed). Additionally, video cameras have been in place since the 1970s for traffic monitoring. The upgrade of the system in the 1997-2002 era became known as IPER-REPER.

On the other side, the signalized arterial network needed a city-wide coordination plan to improve its efficiency: the inner Paris TMC was launched in 1979 to coordinate the central zone, replacing a former system. Today's Poste Central d'Exploitation Lutèce (PCE Lutèce, or Lutèce TMC)was opened in 1989, and additional pools of junctions were gradually wired through the 1980s-2000s, covering most of Paris arterials by 2005. The underlying system is known as SURF, Système urbain de régulation des feux, "Urban system for signals management". The system was aimed at:

- lowering travel-times;

- improving the surface public transport performance;
- ease the movement of emergency vehicles;
- improve ground assets (traffic lights, controllers, etc.) availability thanks to the centralization of alarms raised by faulty equipment.

The system's algorithms rely on fixed road traffic sensors measuring traffic flow variables (flow and occupancy), although additional sensors, not needed by the algorithms, were installed to provide complete traffic state coverage for the TMC supervision. Video cameras were also installed, for a part owned by the Préfecture and for another part owned by the City.

The historical overview of the postwar development of the Greater Paris road network did not only involve road building. The clearly "new supply"-oriented State-funded policy, came along the creation of a technical infrastructure serving the road authorities missions. The goal was to gather in real-time and in a centralized location comprehensive information on the demand over the major routes. This information included the state of assets for users safety (traffic lights, tunnel equipments), the state of traffic (traffic loops). The information on the demand remained closely related to the infrastructure and the authority in charge of it.

This centralized view of the information flows between supply and demand gradually evolved into a model split between several administrative bodies because of several related factors.

One of them is the rising awareness of motor traffic externalities, which has increasingly led to supply-decrease policies for motor traffic, in favor of rebalancing supply to the other road users (surface transit, cycles, pedestrians to name a few).

Another is the devolution process, redefining the role played by the centralized national State and reinforcing local government bodies. Roads do not escape this political shift: the main road network, formerly under the State's jurisdiction which funded most of its development, is since 2006 split between the five aforementioned public road authorities. This means the information infrastructure is also now split between these stakeholders into independent systems.

An additional factor is the sharp reduction of public funding, meaning that road authorities concentrate on their most essential mission: the safety of the users. This means focusing on road maintenance and safety-related assets (traffic lights, tunnels safety). The pressure is even greater since most of the main network's structures were built in the 1960s-1970s and need intensive maintenance.

Finally, the information channel is shifting away from the infrastructure into the vehicles. This does not mean no information will be generated through the infrastructure and its related stakeholders (the road authorities), but the traffic state is better derived if the vehicles themselves produce data relative to their motion, and not only fixed infrastructure based observational spots (the traffic sensors). The floating car data (FCD), which designates information produced by the vehicles, is therefore establishing a relationship between drivers and intermediaries that are independent from the road authority.

1.3 The author's missions and stance

The author's work falls in the context mentioned in the two previous sections: the questioning surrounding the new traffic information three-parties structure and the relationship of the road authority with both the demand and the information intermediaries.

Within the City of Paris, the road authority role is played by the Direction de la Voirie et des Déplacements (DVD), literally the "Roads and journeys administration". In 2016, the City of Paris had an operating budget of €7.8 billion and an investment budget of €1.9 billion euros.

Among this city-wide budget, the DVD accounted for €530 million in operating and €210 million in investment. It had a staff of 1,300 people.

In line with the generic definition of a road authority, the DVD is in charge of managing and operating the public road network within the City of Paris boundaries. The DVD is also in charge of the 100 km waterway network the City of Paris possesses (the latter network extends far out of the City's limits) and of the underground quarries upon which most of Paris is built.

The DVD is split into several departments. The Service des Déplacements (SD), the "Journeys department", is the delegated owner and manager of all required public road assets that are required for managing all modes traveling on the network. Within this department, the PCE Lutèce, officially known as Section études et exploitation (SEE), is in charge of controlling projects and operating assets related to traffic. Traffic is understood as designating all the modes that travel on the road network, even though the original management system was mainly aimed at motorized traffic.

Through the course of his doctoral thesis, the author worked as an engineer at the PCE Lutèce. He namely is a member of the City of Paris Corps of Engineers (Ingénieur des Travaux de la Ville de Paris), created in 1959 with the aim to provide the City of Paris administration with a technical management to drive and operate the City's infrastructure.

He took his position at Lutèce in September 2013 with one main mission: investigate and assess the "new traffic data" provided by the rising traffic information intermediaries, and provide an operational framework for statistical use of these datasets. This mission did not come from nowhere. The legacy fixed traffic information infrastructure both showed a high rate of failure (over 30 % of the total sensors assets), but also failed to answer a key operational issue: assessing the journeys' time across the road network. In other words, it was about assessing, from the demand's perspective (both as a flow and individually), the consequences, in terms of traffic, of major schemes impacting the road network (closure of car-dedicated infrastructures, lowering the legal speed-limit).

The next four years of work involved working with GPS-based Floating Car Data and Bluetooth-based travel-times, from exploring the datasets to delivering technical assessments of traffic conditions based on these datasets. This does not deal with the political aspect of traffic policies assessment, which was out of the author's scope both as an engineer and a PhD student.

1.4 The author's research question

The context described in the previous sections, and the author's missions, inevitably raise the broader questioning, already mentioned, of the future relationship between the three stakeholders of traffic: the road authority (behind the supply), the users (the demand), and the intermediaries (private companies), that catch a growing part of the information flows between supply and demand, and more specifically, the information emanating from the demand. This also puts the intermediaries in a position of manager, competing with the road authority's missions. This is especially true in routing the demand in real-time: the road authority aims at a collective optimum whereas intermediaries are more interested fulfilling the self-interest of their clients. The driver is a user for the road authority, and a client for the intermediary. The intermediary has to prove its efficiency, or at least pretend holding one, in order to be used as widely as possible, in turn collect data, and be profitable.

The scope of this doctoral dissertation does not cover the economical aspects of the traffic information market. It also does not cover the political issues behind traffic-related policies, and neither does it develop a "data-fusion" model that would mix several data sources to model traffic.

It is written from the perspective of the position occupied by its author throughout its four-year mission: it is, from the perspective of a traffic management center in charge of a congested urban network, at the core of one of Europe's biggest and densest cities, dealing with the data generated by the road users themselves. The data is either gathered through intermediaries (GPS speed) or collected by an in-house new type, non-intrusive sensor infrastructure (Bluetooth travel-times). His work was focused on off-line, statistical applications, that then fed the planning and study mission of the City of Paris as a road authority. No real-time applications were covered in the work. This was also a choice of the author, motivated by two main reasons.

The first reason is that in 2013-2014, when he began working on the datasets, these datasets still remained rather new and unexplored outside the research community, especially in France. Road authorities had barely began making use of these new datasets, often on limited perimeters. The author believes he can reasonably assume that the datasets he had access to, which covered the entire City, were among the biggest and richest then available to a road authority in France, both in terms of geographical scope and level of detail. Off-line exploration of the data, in other words, working on archived datasets, is a required preliminary before subsequent software developments.

The second reason is that developing a real-time application requires important technical and financial means. This was unrealistic for the period, and moreover had no political momentum at that time: the issue was getting to know the data before investing more funds. The primary goal was to use the archived data, once it was understood, to assess major political car traffic-related decisions

The author, in his doctoral dissertation, thus addresses the following issue: **from the perspective of a road authority in charge of a road network, what are the metrological and organizational changes induced by the technological shift triggered by the new methods of travel-time measurement?**

Part I

Traffic data and traffic information: linking the Traffic Management Center and the driver

Introduction to the First Part

From the road authority's perspective, the traffic data and traffic information, the latter stemming from the former, are the main link to and from the drivers. Traffic data and information's primary role, which they still retain today, allow to plan and execute improvement works on the road network, in order to provide the best possible "supply" (the infrastructure) to the "demand" (motor traffic), the resulting phenomenon (cars journeying on the roads) being the "road traffic".

Traffic data has backed traffic engineering and traffic-related policies from the early 1920s-1930s investments, to the postwar massive road building programs and the traffic calming policies of the late XXth and early XXIth centuries. It has served road authorities purposes, allowed the inception of Traffic Management Centers.

The evolving technology has allowed to gradually improve the way the data was collected, feeding in multiple theoretical development from the 1930s onwards. The first temporary, experimental spot manned measurements were later replaced by comprehensive, centralized systems. Then, the vehicles and the drivers themselves probed their own journeys, collecting and sending data. Nowadays, in 2017, the latter "new" traffic data is sometimes opposed to the "old", legacy traffic data stemming from spot observations.

The road authority's role can be defined in three points: "maintenance", "planning", and "management".

Knowledge of the users underlies these three points. Knowledge can be retrieved either from the users themselves, or from outside observation, either manned or through sensors.

In order to be analyzed, processed, the collected knowledge needs some sort of standardization: variables, either of quantitative or qualitative nature, are thus defined. The logging of these variables, that translate the gathered knowledge, gradually constitutes data. It must be noted that the relationship between a variable and the device measuring it is complex: either the device can be designed to measure a defined variable, or the type of data retrieved by a device can define a variable. It might even be a combination of both approaches that creates a variable.

"Traffic data" is the set of variables related to the users on the road network.

From the early 1900s to the 2000s, the road authority has focused its efforts on motorized traffic. Therefore, "motorized traffic data" and "traffic data" have become near-synonyms. Likewise, the "traffic" itself does not designate all the categories, but has become a near-synonym of "motorized traffic". Therefore, for the sake of clarity, throughout his work, the author decided to use "traffic" to designate "motorized traffic", and "traffic data", or even "data", to designate "motorized traffic data", except where ambiguity requires clarification. "Traffic variables" that make up the "traffic data" are therefore also related to "motorized traffic" unless otherwise stated.

Means to collect traffic data have evolved. Historically, most of the data collected has resulted from spot-observations (Eulerian data). Nonetheless, the vehicles and drivers can also collect data: at first, this was done experimentally, and then became widespread with the expansion of on-board equipments (Lagrangian data).

Part I thus addresses the following issues:

1. How has traffic data answered the operational needs of the road authorities, and allowed the inception of both traffic engineering and of the Traffic Management Centers most urban road network are headed by? Should “new” traffic data really be opposed to “legacy” traffic data?
2. What have the successive technical advances of the traffic data collection and traffic information broadcasting, from the 1920s to the 2010s, meant for the Traffic Management Centers’ relationship for the drivers? How is that relationship challenged by today’s widespread use and collection of crowdsourced traffic data?

Chapter 2 addresses the first of the above issues: How has traffic data answered the operational needs of the road authorities, and allowed the inception of both traffic engineering and of the Traffic Management Structures most urban road network are headed by? Should “new” traffic data really be opposed to “legacy” traffic data?

“New” traffic data trivially means that another form predated it. Road authorities have been relying on “old” or “legacy” traffic data. In this respect, the author finds necessary to review how authorities built their knowledge of traffic to serve their role as identified above. This is the inception and rise of traffic data. The purpose of this chapter is not to draw the history of traffic theory, as this has been done multiple times [8, 9] and would not be pertinent here. Instead, the chapter focuses on the gradual construction of traffic variables, on the theory that emerged from them, on the way they interacted with the road authority. The author took a chronological approach, relying on selected scientific papers and technical documentation from the United States and France.

This chapter adopts an historical perspective of key studies among the prolific traffic-related literature. The author adopted such way for his literature review because he believed that this way, he could highlight the fundamental operational questions that road authorities have faced in the early days, questions that persist to this day. These questions have received evolving answers as the available means evolved: new roads (conventional highways, expressways), new measurement systems (from manned observations to airplanes to traffic loops to onboard vehicle units), and new theoretical developments to interpret the variables, either measured or inferred.

Chapter 3 addresses the second of the aforementioned issues: What have the successive technical advances of the traffic data collection and traffic information broadcasting, from the 1920s to the 2010s, meant for the Traffic Management Centers’ relationship for the drivers? How is that relationship challenged by today’s widespread use and collection of crowdsourced traffic data?

The chapter puts the traffic data into the broader perspective of the authority’s and Traffic Management Center’s role. It shows that a necessary link between the authority and the traffic is gradually established, and grows steadily. His approach is based on archive material from two major French cities, Paris and Lyon. The work demonstrates that the gradual evolution of this relationship, from an exclusive link to a shared one, and its consequences.

Chapter 2

The "new" against the "old"? The quantification of traffic

2.1 Introduction

Traffic information stems from traffic data. The transformation of the traffic information chain, from a public monopoly based on fixed sensors to a shared public and crowdsourced model using vehicles as probes, is the direct translation of a change in the way the traffic data is collected and defined.

The difference in perspective, between fixed and mobile observation, makes it tempting to oppose an "old" traffic data with a "new" traffic data that would have little to no relation with the former.

From the road authority's position, measuring traffic (in the general sense of "the things moving on the roads it is in charge of") has from the start been a response to a basic operational need: provide the demand with convenient, reliable roads.

The rise of motor traffic, in the 1910s, has marginalized the other users (pedestrians, horse-drawn vehicles, streetcars) in most of the Western world. "Motor traffic" such became "the traffic" or "traffic".

The quantification of traffic, both through time (daily, monthly, yearly trends, and forecasts) and space (throughout the network) became a major tool for all road authorities to fulfill their missions: maintaining the roads, planning their development, and managing the traffic. This meant setting up technical and scientific means, but also seeking some sort of standardization at least nationally, to measure, analyze, study the traffic.

This chapter focuses on the construction of the traffic data as an answer to the operational issues of roads authorities. It shows the progressive definition of traffic variables, but also the means used to measure them: physical variables can often hardly be separated from the devices used to capture them. It also shows that defining the variables paved the way to traffic theory, which became a major tool for managing traffic and planning infrastructures.

The author took a (mostly) chronological approach, relying on selected scientific papers and technical documentation from the United States and France.

The first section, spanning from the XIXth century to the 1930s, shows the inception of traffic data, and the first experimental observations carried out by engineers, who became known as "traffic engineers". From these observations, the first elements of traffic theory stemmed, along with the first traffic stream variables: flow, density, speed.

The second section, within the 1940s-1950s time frame, shows the operational aspect of traffic engineering, and the rise of a need for harmonization, through a selection of traffic manuals published at the time. These manuals allow to identify the issues faced by traffic engineers, and on which variables they focused.

The third section, within the 1950s-1960s time frame, shows how key authors, based on data collected and experiments carried out since the 1930s, moved to provide sound, uniform theoretical background to the variables of traffic. This background gradually yielded the theory of traffic flow, in response to challenges faced by the authority in its understanding of the motorized traffic. Flow, concentration and speed thus become traffic flow variables.

The fourth section focuses on traffic indicators, more specifically two which the author perceived as the most relevant: vehicle kilometers traveled and travel-time. Indicators are closely related to traffic flow variables, of which they give an aggregated view, often more understandable to non-traffic people. The section shows the evolution of the definitions, of the means to measure them, and the purposes they were designed to serve.

The fifth and final section of this part, the Paris case allows to put both traffic flow variables and traffic indicators into perspective with operational needs and technical constraints. It shows the technical implementation of a traffic data collection system and its hurdles, the rise of a profound need for real-time performance data, and the dusk of such centralized collection systems.

2.2 The inception of traffic data: from traffic census to traffic theory, early traffic variables

The XIXth century, with the birth and rise of "modern" statistics, saw the inception of the first "traffic data", for maintenance purposes. Issues raised by the measured and anticipated growth of motor traffic, or more simply traffic, as horse-drawn carriages moved out of the scene, along with the natural curiosity of some people for something new, led to the first observations of the traffic for itself. In the line of these, the need for tools to quantify it led to the first definitions of traffic variables, and the first theorizations of traffic.

2.2.1 Development of traffic data

The oldest of traffic data surely is traffic counts. France started systematic counting campaigns in 1844. The (then royal) administration was facing pavement wear, which was known as being proportional to traffic, but it did not have proper statistics to properly assign maintenance and repair funding to needy sections. The data collected, primarily for road maintenance, became of interest to the State statistics department for various purposes: understanding trade dynamics across the French territory, for instance. A periodic traffic census was therefore established[1]. This was done at specific stations by individuals filling in increasingly complex forms as more categories were drawn [11, 10]. At the beginning, it only classified collars, letting motorized traffic aside. Moreover, in France, until the late 1920s, counting spots were set up in the countryside, as the purpose was to measure intercity traffic and not local traffic. In the late 1920s, with rising congestion concerns, stations were added at the boundaries of cities[2].

In the United States, traffic census are documented in the 1880s. France acted as a reference

[1] Jean Jacques Émile Cheysson, a Ponts et Chaussées engineer, played a key role in institutionalizing the use of statistics: in [10], he mentions that traffic census were carried out, following the 1844 one, in 1851, 1856, 1869, 1876, 1882, 1888, and 1894.

[2] For more information on traffic counting in France, the reader can refer to the work of Dupuy [12].

in the field. In 1906, in Illinois, Dean A.N. Johnson, then a State engineer member of the Illinois Highway Commission, supervised the "commendation for the collection of statistics as to the amount of travel upon rural roads" ([13, p. v]), adding that "no similar data were ever collected in this country, and probably in no other country in the world except France" ([13, p. v]). The operational need for such campaign remained road maintenance and improvement, "since the amount of use actually made of roads determines and justifies the expenditure for their maintenance or improvement". Several other traffic census were carried out in the United States in the years that followed [14]. By the 1930s, the scope of traffic censuses had widened both in data collection and use. For example, as reported by James in 1934 [15], they included the "density of traffic" ([15, p. 57]), "classification of traffic by types of vehicles" ([15, p. 57]), "classification of traffic with respect to the kind of operation" ([15, p. 57]).

All these census were followed by the Advisory Board on Highway Research of the Division of Engineering, National Research Council (in short, Advisory Board on Highway Research), established in 1920, "for the purpose of preparing a comprehensive national program for highway research, to assist existing organizations to coordinate their activities therein, and to collect and distribute information of completed and current research" [14]. Highway traffic analysis was one of the seven research committees part of the board.

The story of the inception of traffic data cannot avoid mentioning W.P. Eno, and the eponymous foundation he created in 1922 and that is still in existence today [16]. He is widely considered to be the father of traffic engineering, which he defined as "the science of highway traffic control consists in the knowledge of how to regulate the movement of vehicles and pedestrians so that they interfere with one another as little as possible and are enabled to go from point to point in the shortest time compatible with safety". Traffic data was a tool to serve traffic control.

2.2.2 The first aerial observations of traffic, and subsequent theorization: 1920s-1930s

Traffic counts remain, even today, the simplest and perhaps most used form of traffic data, and primarily answered maintenance needs. Back in the 1920s, motor traffic was the source of growing interest, but also growing concerns. As "highway research" picked up, new ways of observing were designed and experimented, and along with them, new variables were defined.

Among the growing number of people studying traffic in the 1920s, the already mentioned work of Johnson, who had by then become Dean at the Engineering College of the University of Maryland, provides insight into the state-of-mind of the period. Johnson was concerned by the maintenance and capacity issues caused by increased traffic on the roads, in the line of his 1906 traffic census in Illinois [13]. In 1925, he presented a work on "Elements Governing the Development of Highway Traffic" [18], in order "to discuss the amount of future traffic upon American highways and to compare this with the traffic capacity of a two-lane road" ([18, p. 259]). Johnson considers "highway traffic" ([18, p. 259]), and the standard road is a "two-lane road" ([18, p. 259]). He takes a global, network-wide approach, in which three quantities he calls "physical facts" ([18, p. 259]) qualify "highway traffic" ([18, p. 259]): "the number of vehicles using the road in a given time" ([18, p. 259]), "the road mileage made by these vehicles during some definite period" ([18, p. 259]), and "the mileage of the system of highways upon which the traffic moves" ([18, p. 259]). The amount of highway traffic on the network refers to the "density of traffic over a system of roads" ([18, p. 259]). With in mind hydrodynamic considerations that will be given to traffic a few decades later, density here is already an idea linked to considering a pool of vehicle over a road segment.

In fact his study considers two scales, the scale of the vehicle and the scale of a pool of vehicles. These two scales are mentioned, indirectly, in his description of congestion, although he concedes that traffic congestion may be found over "some sections of certain highways where traffic concentrates", these sections "carry[ing] nearly their capacity and frequently are taxed much beyond it" while making up only "a small fraction of the total mileage of the State highway systems". Congestion, and its forecast, translates into an infrastructure variable, the "capacity": what is the "ultimate capacity of highways for the widths generally built at present", and how it compares with traffic growth forecasts. JOHNSON draws capacity estimates for one lane of traffic, which he calls "the total discharge of a single lane of traffic", or what we would today call lane capacity. Again, the approach considers both per-vehicle and flow approaches, the scales of which are not directly mentioned. JOHNSON identifies two key variables at stake behind the lane capacity: the vehicles' "velocity" V, and the "spacing or intervals between the vehicles". The spacing between two consecutive vehicles is the sum of two quantities, the vehicles length (assumed to be homogeneous) and the "the clear distance between vehicles", or "clearance" C. JOHNSON thus proposes a formula that links average quantities describing the population of vehicles (average length, average velocity V, average clearance C) with flow ("the number of vehicles discharged per hour" or "the number of vehicles that will pass a given point in 1 hour", as the time basis for his computations is 1 hour). An experiment to study the "capacity of a two-track highway" was carried out on the Washington-Baltimore Road in 1924: counts were made by different observers at various locations alongside the corridor. Congestion is defined qualitatively, "when a faster moving vehicle could not conveniently pass a slower one". Observed data was confronted with the formula he had elaborated, and then used for his estimation of "the average daily traffic that may be maintained throughout the year" on the road.

The Washington-Baltimore Road will still play a role in subsequent JOHNSON's work. The July 4th, 1927 aerial campaign of the State Roads Commission of Maryland [17] over this corridor is one of the earliest reported works that brings traffic study beyond simple vehicle counting or ground-based, roadside observations. The operational need behind the air survey was the study of traffic characteristics along the Baltimore-Washington corridor, due to be widened "from 20 feet to 40 feet"[3], but also to investigate the possibilities offered by such observation technique. Most of his previous work relied on fixed point observations. The 1927 aerial survey raises, although not always explicitly, ways of observing and characterizing traffic that remain in use to this day.

During this experiment, traffic was sensed through three means: 1. from the air, with an aircraft fitted with a picture camera; 2. from the ground, with four traffic stations (with two observers, each counting one direction of traffic); 3. from both the ground and the air, with six identifiable vehicles driving along the corridor while photographs were taken. When considered with modern eyes, but also reading JOHNSON's position, these three means already account for very current concepts.

The four traffic count stations are a classic mean of traffic observation, with already more than two decades of practice in the United States.

The 127 exposures made from the aircraft overlapped, and "as many vehicles flowed on as flowed off the road", hence there was a nearly uniform traffic volume on the considered corridor. This argument is key for JOHNSON to consider that the successive photographs taken through a period of 27 minutes accounted as if "possible to take at a single instant a photograph of the traffic of the entire road". From the aerial pictures considered as a still instantaneous view of the

[3] i.e., from 6 to 12 meters.

road, JOHNSON computes a spatial "traffic distribution", which he sees as "uneven". JOHNSON is conscious of the novelty of his findings: "the aerial photographic survey of traffic affords a mean of making far better observations than is possible otherwise".

Cross-analyzing the traffic counts with the spatial distribution, JOHNSON makes a key operational comment. He compares the average flow of vehicles, which he found to be below the threshold at which the road begins to be "inconvenient for the faster moving vehicles to overtake a slower" (i.e., congested), and the spatial density (number of vehicles per quarter of mile). Yet he observed "serious congestion at great many points": the uneven spatial distribution of vehicles, with only half the road "crowded". His conclusion: "how inefficiently the traffic made use of the roadway". Today's use of the roadway can still be questioned as we face major congestion issues, although exceeding the 1920s levels. Nevertheless, today, the spatial side is complemented by the vehicle occupancy issue. Schematically, today's spatial issues are expected to be solved by a greater automation of vehicles, which are believed to guarantee the best possible use of the roadway by smoothing headways. Vehicle occupancy, as most people are alone in their cars, is addressed through various incentives, from dedicated lanes to financial bonuses. JOHNSON made the inefficient road use a key point of his work: "a conclusion to be drawn from the aerial traffic survey is the importance of any regulation which will tend to greater uniformity in the distribution of traffic and that whatever will help to do this will to that extent increase the efficient use of the road."

The aerial pictures allowed JOHNSON to fine-tune his previous observations on clearance and vehicular speeds. What would be later called the fundamental diagram was here drawn as the "relation of discharge to velocity". Two successive overlapping exposures could be used to track "the same group of vehicles", "displaced by the distance that they have traveled between the times of the successive exposures".

While the road was being photographed, specific identifiable vehicles were driven along it. "Six cars were fitted with white tops by stretching a sheet over them, and a driver and observer in each. These spot cars, as they were called, were timed to enter the traffic on the road so as to be photographed at various points" ([17, pp. 106–108]). Their drivers had very specific instructions in order to reflect the general traffic conditions they were in: "The drivers of these cars were instructed to drive with the traffic, not attempting to pass slow moving traffic, nor to hold up traffic". The observers were in charge of logging the speed: "The observers made frequent observations as to the speed of traffic [...]". This setup recalls the later floating car concept: consider a vehicle equipped with a GPS receiver that keeps track of its coordinates and speed. A report of its coordinates is in analogy with a picture taken from the air of its position on the road. A report of its speed is in analogy with the speed logged by the observer on board the vehicle.

JOHNSON is aware of the limitations of his experiments: he reports scaling issues with the photographs, as well as not having the exact timestamp of each photograph: "the facts are that the scale of the different photographs varied somewhat, as well as the interval between exposures". Nonetheless, his work had somehow formalized the observation of key traffic variables. Figure 2.1 shows, in an $x - t$ plane, the various variables studied by Johnson.

JOHNSON's reported "distribution of the traffic" seemingly triggered, at least for a part, more research on stochastic considerations of traffic, while at the same time JOHNSON and others tried to come up with one-curve relationships between traffic variables (namely clearance and speed).

These works on the use of probabilities are among the earliest efforts to theorize traffic. KINZER [19], based on JOHNSON's observations, conceived a stochastic model for traffic: a Poisson law for the spatial distribution of traffic (number of vehicles per segment of roadway). As

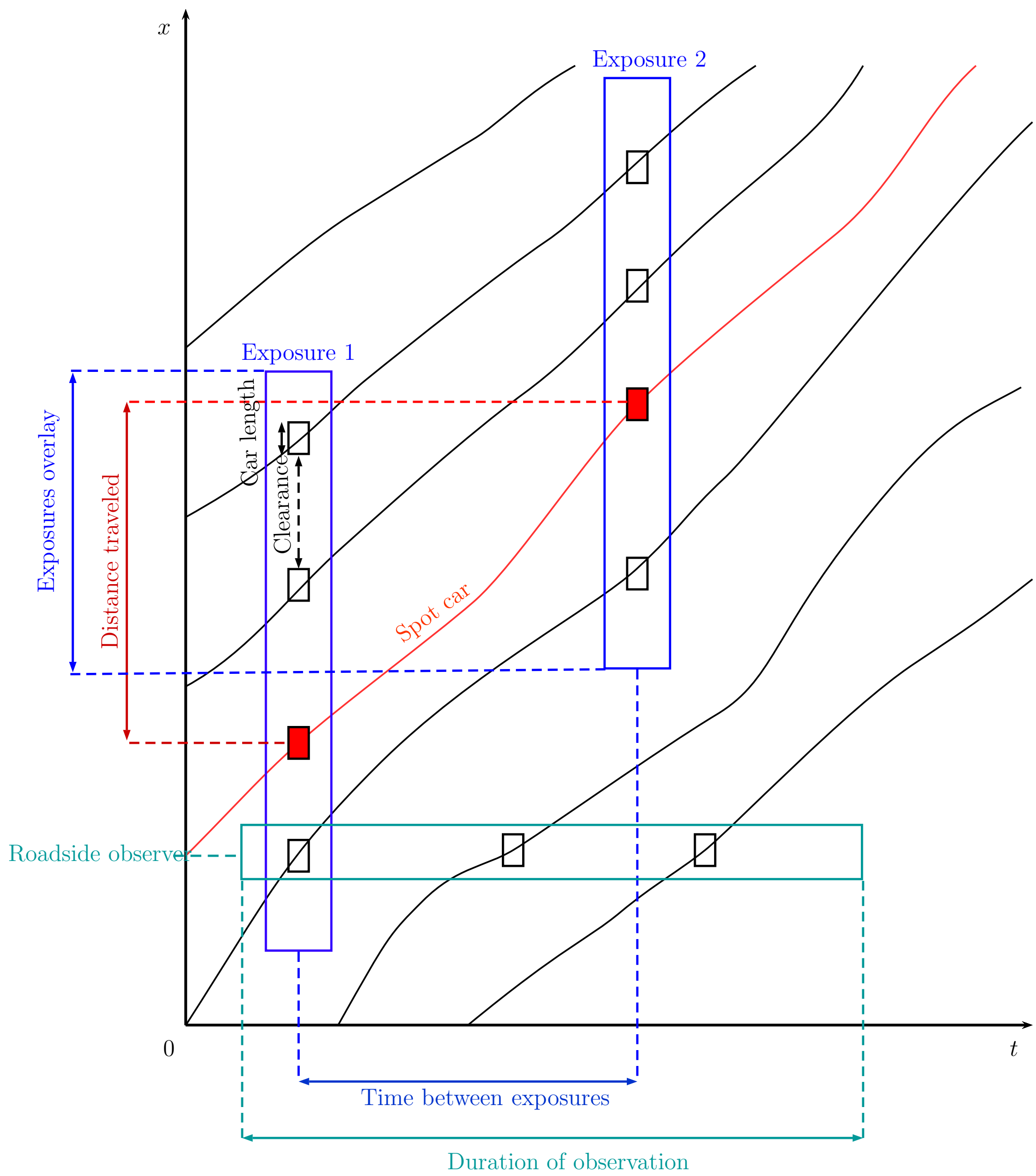

Figure 2.1 – Traffic variables at stake in Dean A.N. Johnson's traffic study [17], drawn upon an $x-t$ diagram.

discussed by Buckley [20], Kinzer's wrongly justified his assumption by the independence of counts between two successive sections of roadways. Adams offers, in the line of Kinzer's work, a well-formalized treatment of traffic as random series [21]. Adams introduces his theory by making an analogy between road traffic and "a distribution of points along a line". By doing so, relying on the theory of probabilities, he formalizes the two ways of observing traffic:

- One point can first represent "the position of a vehicle at a given moment" and a line "a length of road": this theorizes the observations made from the air by Johnson and the distribution of traffic per section he drew. In other words, this is a picture of traffic over space at a given time.
- The line can represent "a period of time" and the points "the moments at which vehicles passed a given place."

In this theory of probabilities' perspective, a point is an "event".

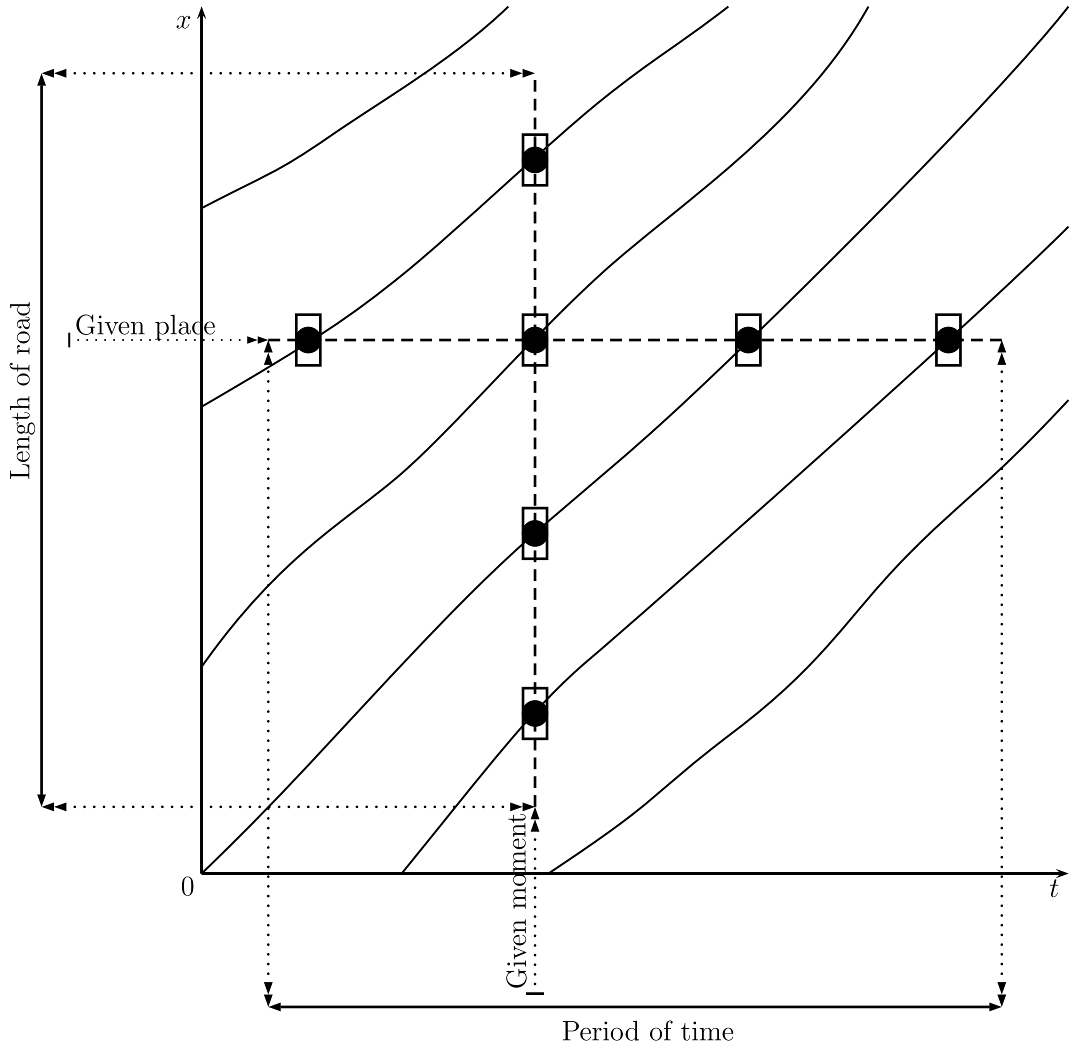

Figure 2.2 – Traffic variables at stake in Adams*'s traffic study [21], drawn upon an $x - t$ diagram.*

Adams, "[having] collected a large volume of evidence", assumes "that under normal conditions, free-flowing traffic corresponds very closely to a random series of events." He justifies randomness by the independence between two successive events, and that equal intervals of observation (either taking a time or space perspective) are "equally likely to contain equal numbers of events". He then calls upon the "Theory of Probability" to propose Poisson's law as describing the counts in free-flowing traffic. Whereas Johnson worked on an interurban corridor, Adams collected his data in a very urban environment, namely the streets of London.

Although Adams mentioned both either time or space perspective to observe traffic, his work here relies on fixed-location observations. He backs two empirical traffic data on Poisson's law and its affiliate, the exponential law.

He at first considers traffic counts by referring to the "Theory of Probability". Traffic is observed at a specific spot, and the arrival of a vehicle is thus an "event". "It is shown that for a random series, the probability of any given number x of events occurring in a given time is given by" Poisson's law formula:

$$P(x) = \mathrm{e}^{-\lambda}\,\frac{\lambda^x}{x!} \tag{2.2.1}$$

with $P(x)$ being "the probability of x events occurring", and λ the "mean number of events expected in the given time"[4].

When confronting his empirical data with Poisson's, ADAMS takes an original approach, at least as far as the traffic domain is concerned. From the $P(x)$ expression, he then considers traffic from the time frame perspective, i.e., if "n equal periods of time were considered, the probable number of these periods in which x vehicles arrive is $n \cdot P(x)$".

During his field experiment, he counted vehicles for one hour at different locations, dividing each hour into 10-second periods. He plotted the number of observed vehicle per 10-second period against the corresponding number of 10-second intervals, both for the empirical data and the theoretical (given by $n \cdot P(x)$). He found that "freely-flowing traffic normally conforms to the above law". He added that "the agreement in these and in many other similar cases", meaning that ADAMS did in fact carry out numerous field observations, "is sufficiently good to justify the working assumption that road traffic is normally a random series". The semantics of this last sentence are key: the purpose is not find a perfect model, but to find one that answers operational needs.

Poisson's law triggers a fundamental result: the law of the intervals between two events underlying the counting process. ADAMS was aware of it, and offered a theoretical definition of "the lengths of intervals of time elapsing between the arrival of consecutive vehicles", what would later be known as vehicle headways. The "Exponential Law of Intervals", as he labels it, yields "the number of intervals greater than t seconds":

$$a \cdot \mathrm{e}^{-Nt} \tag{2.2.2}$$

with a "the total number of intervals considered" and N "the average number of vehicles per second". Again, field data backed the theoretical assumption.

ADAMS's theoretical development, which we today designate as a Poisson process, is one of the earliest studies, in the field of traffic, linking by theory the vehicle scale (later known as microscopic scale) with the flow scale (later known as macroscopic scale), by the means of purely theoretical tools. JOHNSON, on the other hand, backed his relationship between the vehicle scale (observed through the "clearance" between two successive vehicles and the speed of vehicles) and the flow scale (vehicle count) on field data. In a first observation campaign in 1924 [18], JOHNSON stated that "there is some evidence [...] to indicate that the spacing between the vehicles varies approximately as the square of the velocity". After the 1927 aerial campaign, he reported [17] that "from these observations, it is shown that the clearance varied approximately as the 4/3 power of the velocity". At the dawn of traffic theory, we see here two approaches on traffic data. On one hand, JOHNSON's, essentially field-based, who derives relationships between traffic variables directly from the field data. ADAMS's approach, on the other hand, is held by the Poisson theory, which allows the seamless transition between the two scales.

The Poisson theory was already used in the telephone industry, triggered by the studies made at the Telephone Company of Copenhagen by JOHANNSEN and ERLANG, who published a first account of their research in 1909.

Well aware of the Poisson theory usefulness, and in relation with the telephone industry, reporting that "the theory of telephone traffic has provided many suggestions", ADAMS investigated its operational usage for traffic. The case presented are of course closely related to ones in the theory of telephone traffic: for instance, in 1909, ERLANG computes the "probability of a certain number of calls being originated during a certain interval of time", whereas ADAMS computes

[4] The author chose to use λ for the modern eye, although ADAMS used the letter m in his paper to designate the mean number of events in the given time.

the "probability that just x vehicles will arrive in a given time".

From these probabilities Adams is able to solve various operational problems: estimate turning volume at a signalized junction, find the proper timing for traffic lights, computing the average delay of a pedestrian crossing a road. Greenshields, Schapiro, and Ericksen [23] will a decade later underline the importance played by the Poisson theory in solving "traffic problems that otherwise would be very difficult, if not impossible, to solve" ([23, p. 83]). Hence, two simple traffic variables, count and time headway, along with the random series assumption for free-flowing traffic, allowed developments that are, Adams himself concedes, "rather remote deductions". He also seriously questions the free-flowing nature of traffic. Nonetheless, at his time, "traffic flow in streets is very rarely saturated", and he had "some difficulty to obtain observations" of saturation.

2.2.3 The work of Greenshields: 1930s-1940s

The work of Greenshields is a major step towards "modern" traffic theory, and the underlying data and variables. He developed various equipments to measure traffic. Greenshields was very keen on producing manuals that could be of use to traffic engineers, and the prefaces of his various works are particularly valuable for understanding the context in which theoretical foundations to traffic engineering were established.

One of Greenshields's earliest works, "The photographic method of studying traffic behavior," published in 1934 [24] as part of his Ph.D. dissertation at the University of Michigan, focused on "securing accurate data on traffic behavior". Behavior usually refers either to a person, a machine or a phenomenon: traffic had in fact become something to worry about, hence to study. Operational needs were there, but besides traffic counts or costly air surveys as done by Johnson, not much was available to measure traffic. Using "behavior" underlines the fact that traffic had become a complex phenomenon, and that its complexity meant that counts were just not enough to gather knowledge of its dynamics. From the start, Greenshields anchors his "photographic method" work on operational grounds. He points the crucial aspect of data collection ("securing the accurate data on traffic behavior"), "which are necessary for the design of streets and highways with adequate capacity and for the regulation of traffic".

His photographic method is a spot-observation, but could also be considered as a ground "air survey", taken from the side of the road and not from atop. The raw data it produces is an *instantaneous record of the position of the vehicles*, through photography, each taken at regular time intervals. The length of road covered by the camera field is "about 125 ft" ([24, p. 384]), i.e. about 40 m. From either an individual photograph or succeeding photographs, vehicular speed V and spacing S between vehicles centers can be deduced, as Figure 2.3 shows. These are the same variables as obtained from Johnson's campaign (between two successive shots), but whereas Johnson accounted for the variabilities of his measurements (scaling issues, approximate timestamp of exposures), Greenshields made a point of obtaining the greatest measurement accuracy as possible. Each exposure was timestamped, and the scale of the photographs precisely recorded. Most of Greenshields's work in the years that followed relied on this "photographic method".

Greenshields, much like Johnson, investigated the spacing S and speed V relationship, from which operational issues such as traffic safety (minimal breaking distance) and road capacity can be derived, as previously stated by Johnson. Moreover, investigating the $S-V$ relationship allowed Greenshields to show the relevance of his ground-photography technique, as the topic had already been studied since the 1920s. Another step taken by Greenshields is the physical interpretation of the formula he derived from his observations: he assumed the formula was the result of other variables directly linked to the driver as an individual. In a section titled "Rationalizing the equation", GREENSHIELDS writes: "it was felt the equation should contain terms for: 1. the spacing of cars with a velocity at or approaching zero; 2. an allowance for the distance traveled during the reaction-time of the driver and; 3. possibly a term which would take account of the caution or judgment of the driver ".

Drivers' reaction-time was already seen as a key factor explaining the spacing between cars. Drivers' reaction time studies are beyond the scope of the author 's work, who will just note that variables describing individual behaviors such as reaction time were already in the scope of engineers and researchers. Several studies, already in the 1920s, had tried to quantify the "brake reaction-time" in what was called the "the personal equation in automobile driving" [25]. GREENSHIELDS started looking into reaction-time as he hinted its deep relationship with how vehicles were spaced on the road. This shows how traffic was considered from the individual perspective to the larger scale (vehicle counts) within the same study, hence the paper's title: "studying traffic behavior".

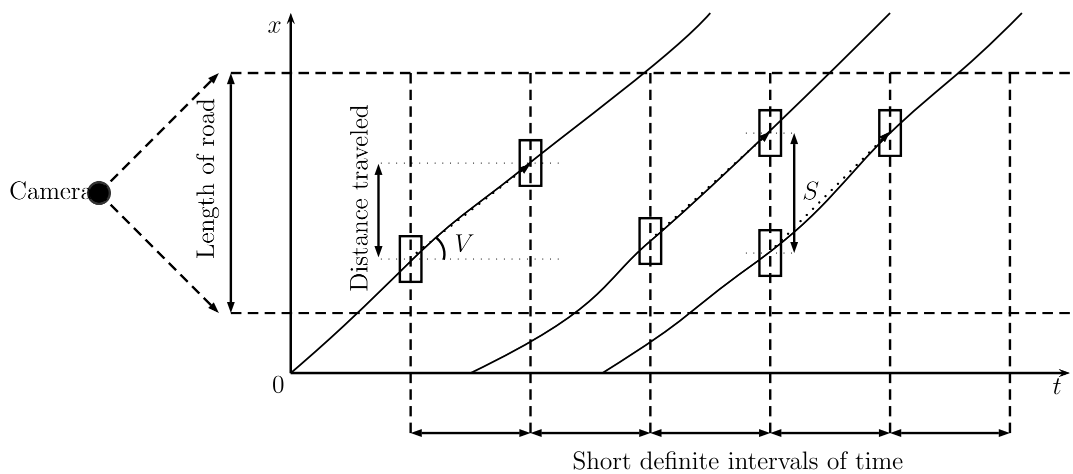

Figure 2.3 – Traffic variables at stake in GREENSHIELDS*'s photographic method [24], drawn upon an $x-t$ diagram.*

Following the successful setup of the photographic method, and his studies of driver's reaction time and vehicle spacing, in 1934 GREENSHIELDS investigates, in what became a seminal paper, "traffic capacity" [26]. He takes the notion of capacity from JOHNSON, who, in 1931 [27], proposed an early definition of it: "We can visualize a road carrying but a few vehicles and agree that there is no congestion. But as the number of vehicles increases, there will be a point reached at which some vehicles will be delayed because they are immediately unable to pass other slower moving vehicles. Such a point indicates the beginning of congestion or what may be called 'working capacity' or 'free moving capacity' of the highway" ([27, p. 218]). GREENSHIELDS will also call it "carrying capacity". In other words, capacity, a characteristic of the infrastructure, now defined, and separated, two traffic states: traffic without or with congestion.

GREENSHIELDS's study of capacity solely relied on per-vehicle observation, using the photographic method, the camera being triggered at a frequency of 88 shots per minute. With such a rate, the same vehicle would be pictured at least twice, yielding the measurement of its speed over a very short distance. As "practically 100 per cent of all vehicles passing the points of observation" were pictured, volume (then also called density) could easily be deduced. Pictures being taken at fixed intervals, speed for each vehicle was computed, like previously [24], by "noting the distance each vehicle traveled during one of these time intervals".

The individual vehicle data was then tabulated into groups of 100 cars, and the average speed taken as a moving average by a step of 10 over 100 cars (i.e., one average for 0 to 100, then for 11 to 110, then for 21 to 121, . . .). The average done was most likely arithmetic, although no explicit mention of the type of average is made. As for the step length, set to 10, it was "chosen arbitrarily", with no further justification. What's fundamental here is that GREENSHIELDS worked with averages and not directly with individual vehicles data. Without explicitly mentioning it, he was positioning his theory at a scale which would become the macroscopic scale. He nonetheless justified the fact of aggregating vehicular data into groups not because it was easier to process aggregates (as one would have perhaps expected to read, given the limited computational power available at the time), but because of a "fundamental statistical principle that in plotting and drawing a curve [...], the data should be 'smoothed' to eliminate the accidental irregularities as far as possible, before being utilized". He adds: "this means drawing the smoothest curve possible through the plotted points", which were already the results of averages. This argument against the variability of the data, which needs to be smoothed, is not justified any further: GREENSHIELDS instinctively sought a smoothed, "good-looking" curve.

The hydrodynamic analogy [28, 29, 30], which allowed to precisely define flow, density and speed in the early 1950s, is also implicitly mentioned through his dual definition of the density. The density he effectively measures is now known as flow. When "deriving the equation for expression of relation of speed and density", he finds "convenient" to express the densities "in vehicles per mile of pavement". He adds, "this density, D' is found from D, the density in vehicles per hour by dividing D by the average speed in miles per hour". Most likely, dimensional analysis triggered this thought, although some knowledge of the fluids mechanics may also have played the role in hinting this relationship. It is interesting to note how this terminology emanated from roadside observations, as *traffic density* designated two different quantities, now known as flow (or, in GREENSHIELDS's words, "D, the density in vehicles per hour") and spatial density (or, in GREENSHIELDS's words, "D', the density in vehicles per mile of pavement"), only the units allowing to distinguish the two.

His reasoning yields him to key traffic variables that allow "to determine the effect of congestion for all different densities": with limited means to measure traffic, this had strong operational consequences. The "straight line" linking the "speed" and "average density in vehicles per mile of pavement" only requires "two points to fix its direction", "the free speed" and "a point near the maximum density". From this relationship GREENSHIELDS computes a still fundamental indicator, the "the time lost in minutes per vehicle per mile", and its aggregation, "the total time lost for all vehicles per mile".

Operationally, the density D is easier to measure than D', but it poses problems when wanting to evaluate the time lost, as "there are two speeds at which the same density may occur". GREENSHIELDS circumvents the difficulty by assuming that "it is necessary to know the approximate spacing between vehicles" or "whether the road is loaded beyond its maximum carrying capacity", in order to then identify "which part of the curve to use in estimating the time loss". He more or less implicitly assumes the universality of his relationship and its operational usefulness, despite the parameters' estimation remaining a hurdle, as for instance he shows their variation relatively to the percentage of trucks.

The discussion that follows the paper offers an insight on other speed measurement experiments, hardly documented elsewhere in the mainstream literature. GREENSHIELDS manipulated average speeds, most likely arithmetic averages, taken over groups of vehicles at a specific location, over a very short segment of highway. ROWLAND BIBBINS [31] questions GREENSHIELDS speed definition, and reports what is perhaps one of the earliest documented vehicle re-identification travel-time measurement campaign. He describes his technique as "the simple method of getting *over-all* speeds over a stretch of highway by recording the tag number of the vehicle entering the stretch and checking the *same* tag number on leaving" ([31, pp. 474–475]). A team of observers positioned along a section of the Lake Front "express highway" ([31, pp. 474–475]) in Chicago recorded tags, by intervals of 5 to 10 seconds. For reasons not stated in his statement, the measurement campaign was challenged in court, and the author concedes that he "had some difficulty in substantiating the accuracy of the test because it was not a 100 per cent count" ([31, pp. 474–475]). Such campaigns would be successfully carried out by automatic devices decades later, but the same points would be again risen against them: what is the relevance of catching just a part of the traffic (as not all vehicles can be matched, especially if there are exits in-between), whereas methods such as aerial views or roadside spot measurements virtually catch all vehicles that pass through the area of observation? ROWLAND BIBBINS had a great intuition in measuring travel-times as he did, and shows once again that the notion of speed, either "over-all" speed or "spot speed", was already questioned in the early days of traffic.

As JOHNSON's and GREENSHIELDS's early works show, speed already represented a key operational variable. If the works of both of them is valuable, the techniques involved (air survey, automated camera) remained quite complex. They probably knew it. Professor C.J. TILDEN, of Yale University, came up with a simple tool to measure vehicles speed from a roadside location. The device was referred to as the "ENO Foundation speed detector" and very simple to use, simply involving a human observer at ground level, and a static box with two openings and a mirror. The speed retrieved with this tool is very similar to the one retrieved through today's dual loop systems: the measurement is indirect, as speed is deduced from timing and distance measurements. In the 1930s, several States carried out "highway traffic speed surveys". The Maryland State Roads Commission's, reported by JOHNSON [32], made use of the ENO speed detector over fifty stations: all were already defined for the traffic census. This underlines the importance of continuity of traffic statistics, even in the early days. Other states had police patrols driving in traffic, "pacing" vehicles and recording speedometer values, as reported in the Discussion of [32] for the State of Michigan. Such campaigns helped the States on various operational issues: drivers' compliance to posted speed limits, performance of the highway system, effects of road widenings (although for Maryland, JOHNSON conceded that "no convincing results" were gathered regarding that latter point).

Most of the variables described above were observed in an interurban setting or on expressways. Nonetheless, the urban environment had been actively studied. The aforementioned W.P. ENO had been involved since the beginning of the century into the regulation of traffic, cooperating with police forces and municipal administrations worldwide. The primary concern was to establish proper regulations and layouts to accommodate growing traffic. In 1947, the first of a series of Technical reports by the Yale Bureau of Highway Traffic was published, *Traffic performance at urban street intersections* [23], presenting, as its title suggests, the results of a wide-ranging study regarding urban intersections. This can be considered the first comprehensive application of traffic theory to an urban setting. Among its authors stands the well-known GREENSHIELDS. The study capitalizes on the past twenty years of traffic observations and publications, but also aims at taking the observations into a more integrated and rigorous approach, as the preface states: "thorough knowledge of intersection performance cannot be gained from casual observations of the many contending factors". The study, like many of GREENSHIELDS's previous works, gathered its data from his "time-motion" technique, formerly known as the "photographic method". Again, both the time and space dimensions were considered, as he already stated in the book's preface. Assumptions and "basic laws" are, in terms of scale, worked from top to bottom. The photographs allow per-vehicule observations, and subsequent analysis is carried out "to measure the range of values which arise from the variability of the human and vehicular factors inherent in the road users and their vehicles". The variables measured in the report are for the most part not new, and were already approached in various research works since the 1920s ; the report is key on the way it considers all of the variables together under the same observation technique.

Much like previous uses of the photographic method, the successive pictures only yielded the vehicles trajectories upon the observed intersections; a superimposed grid and a time counter allowed to keep track of time and quantify the vehicles' location. From these sequences of pictures, acceleration, deceleration, reaction-time, time and space gaps could be deduced. These variables are defined at the vehicle's scale. The "formulation of basic laws" is done through taking the average or median of the resulting distributions of measured values. The authors also define variables at the scale of the flow of vehicles, but infrastructure-related, mainly the "intersection's capacity": "the capacity per lane of any green period is measured by the number of vehicles which can enter the intersection during the period" ([23, p. 26]). Moreover, the link between the vehicle and traffic scales is funded on the Poisson theory: "Road traffic conforms so well to Poisson's random series that its application leads to results of practical importance." ([23, p. 109]) Greenshields acknowledges the work done by Adams a decade earlier, who wrote him to "point out the application of the Poisson series in [traffic] studies." ([23, p. 77]) Prolongating Adams's work, the report relies on Poisson to theorize the observations. Sign that much of the observational and theoretical work undertaken held a sharp operational focus, the last chapter of the report is dedicated to "Typical Traffic Problems" ([23, p. 111]) in order to "illustrate the application of the methods". The theory of probability (through Poisson) allows to solve "traffic problems that otherwise would be very difficult, if not impossible, to solve" ([23, p. 83]), as the author already mentioned.

Road maintenance and improvement were from the start the key motivations behind traffic data collection. As a link was drawn by road authorities between road condition and the volume of traffic, traffic count became the first of traffic data to be methodically collected.

Rising traffic demand yielded an additional question: how many cars could a highway cope with? Congestion became an issue, and capacity gradually a variable to estimate it and quantify the needed improvements on the infrastructure.

Road and traffic research is institutionalized, in the line of the Eno Foundation, and multiple experiments are carried out to observe and quantify traffic. Works by Johnson, followed by Adams and Greenshields, yield first definitions of vehicle gap and headways, velocity, density, volume, although the terminology of the time is not necessarily the same as today's. In an effort to quantify and predict congestion, first investigations are carried out on the relationship between velocity and density, velocity and volume. The first theoretical background is given by the theory of probability.

Two means of observing traffic were experimented: ground-based spot observations and aerial observation. Both of them yielded their set of definitions, and already raised the dilemma posed by these two methods. The road authority wants to have thorough knowledge both in space and time of the traffic on its network.

Spot surveys are "cheap" but only provide data at a specific location over periods of time. Aerial surveys provide much more extensive spatial information, but at great cost and only at a specific time.

These works aimed at understanding and quantifying traffic for road maintenance and planning reasons. Theory could help plan future behaviors without necessarily requiring extensive measurement campaigns that were tedious and expensive.

During the two decades that followed the war, from the 1940s to the 1960s, much of today's traffic variables were precisely defined, based on experience gathered from the early twentieth century and the refinement of observational techniques.

2.3 The era of traffic engineering manuals: 1940s–1950s

The 1940s and 1950s saw the publication of the first introductory or comprehensive traffic engineering manuals, often brought forward by the various, and somehow competing, institutions or foundations created at the dawn of traffic science to help authorities at various levels in dealing with the automobile. These were primarily designed for traffic engineers, or engineers that had to cope with automobile. Much of the early work was done by Eno through the Eno Foundation [33].

The move was initiated in 1941 by the Institute of Traffic Engineers [34], followed in 1950 by the *Highway Capacity Manual* of the Highway Research Board [35], which primarily dealt with capacity, as its title suggests. Another manual, by the Bureau of Highway Traffic, followed in 1955 [36], much in line with the Institute of Traffic Engineers manual. Meanwhile, Greenshields and Weida, in 1952 [37], had provided a manual with a stronger theoretical anchoring, dealing with statistics and traffic data.

2.3.1 The Institute of Traffic Engineers' 1941 *Traffic Engineering Handbook*

The Institute of Traffic Engineers, officially established in 1931, issued its *Traffic Engineering Handbook* in 1941 [34] jointly with the National Conservation Bureau, which later on became the Accident Prevention Department of the Association of Casualty and Surety Companies.

It is introduced both as "the first ever to be published", and "not [with] the purpose to serve as textbook on traffic engineering". "Instead its purpose is to collate in one volume basic traffic engineering data as a guide to best practice in those portions of the field in which well-accepted principles have been established". At the time, most of the traffic engineering literature was split between "pamphlets, reports, and articles in professional journals, each covering only a limited portion of the field". The manual is dedicated to engineers.

Traffic variables of the time are defined within the "Traffic Studies and Surveys" chapter [34, pp. 64–87]. It is preceded by four chapters respectively defining "The Motor Vehicle" (figures on its use, its consumption), "Vehicle Motion" ("the natural laws of motion as they apply to motor vehicles" ([34, p. 11])), "The Driver" ("Facts concerning the age, sex, and physical and mental characteristics of these drivers" ([34, p. 27])), "The Pedestrian" ("chief aspects of the pedestrian problem [...] concerning sidewalk capacities, pedestrian volumes, speeds and accidents." ([34, p. 34])), and a fifth on "Traffic Accidents Records and Indices" ([34, p. 56]).

The "Traffic Studies and Surveys" ([34, pp. 64–87]) chapter identifies several categories of traffic variables, among which "vehicular volumes", "spot speed studies", "speed and delay", and "origin and destination".

2.3.1.1 Vehicular volumes and the Short Count method

The first category of variables is the *Vehicular volumes*, "the enumeration of vehicles passing a selected point during known periods of time" ([34, p. 66]). A technique to measure it is presented: the "short count method", documented in a 1935 publication, *Short count traffic surveys and their application to highway design*, by the Portland Cement Association [38]. This report offers an insight of the traffic data collection issues faced by engineers in the 1930s, and the needs fulfilled by traffic data. It opens by an address of the President of Portland Cement Association "to highway engineers and officials" ([38, p. 3]), reminding them of "the importance of traffic data as a guide to rational highway and street planning and economical design of pavements to carry anticipated loads" ([38, p. 3]), but that cost and time remained a hurdle for data collection campaigns: "there has been needed a speedy and economical method of securing and interpreting data information" ([38, p. 3]). Of course, the report being published by a cement company, pavement is mentioned, but the traffic data issue for highway funding nonetheless remained. In the report's first chapter, "Utility of Traffic Data" ([38, pp. 5–8]), McClintock reminds that "progressive highway agencies – local, state and Federal – are increasingly insistent that highway planning and construction be based upon adequate traffic data" ([38, p. 5]). The Great Depression was also part of the equation, as it "has made it imperative that every dollar be made to go as far as possible" ([38, p. 5]), as "taxpayers show more resistance than ever before to highway expenditures which cannot be justified by demonstrated needs" ([38, p. 5]). McClintock also underlined the traffic data importance for the highway engineer, "who [...] without adequate facts regarding the traffic requirements of the area for which he is responsible is in constant jeopardy" ([38, p. 5]) and then "has little or no protection against political importunities" ([38, p. 5]). Traffic data already held both an economic but also political interest. McClintock's short count traffic surveys method aims at answering the two usual obstacles that have prevented traffic data collection: "the complexity of counting methods" ([38, p. 6]) and "cost" ([38, p. 6]). Up to then, traffic studies that were carried out required 24-hour measure at each counting station. From studies of traffic surveys carried out across the United States, McClintock postulated two principles:

1. "the percentage of total daily traffic occurring in any given hour is approximately constant at different points along the same route, or on routes of the same character in the same district or region" ([38, p. 9]).
2. "the total volume of traffic does not vary materially as between normal week days, Monday to Friday, inclusive" ([38, p. 10]).

These two simple ideas allowed him to propose a lighter traffic survey apparatus, relying on two types of counting stations:

long count or control stations , where "traffic is recorded by hours for a full 24-hour day [...] for the purpose of determining how the total daily traffic is distributed to the various hours of the day" ([38, p. 13]).

short count or base stations , where "traffic is recorded for one hour, morning and afternoon, only" ([38, p. 13]). Proportionality rules are then used to transform hourly counts into 24-hour counts.

The method was given ample publicity, as it was repeateadly mentioned in forthcoming traffic engineering manuals.

Volume counting traffic surveys results were typically presented on "traffic density maps". Density was indeed still ambiguously used to designate both spatial density (the modern sense of traffic density in traffic engineering) and volume.

2.3.1.2 Spot Speed Studies

The manual defines "spot speed" as the "measurement of the speed of vehicles passing a selected spot of relative short distance usually not exceeding 375 ft" ([34, p. 69]), i.e. around 110 m. Today, spot speed would be in most cases measured on a distance of at most 10 meters. They were aimed at showing "the distribution of speeds which prevail under varying conditions" ([34, p. 69]).

Speed was quickly linked to traffic safety issues, and the manual makes no exception: it does so by referring to a report by the National Safety Council on *Speed regulation* [39] for speed measurement techniques.

Various ways were devised to measure speed for engineering, safety or research purposes. Among these means, those commercially available to engineers for wide traffic surveys are identified in the various reports that deal with speed surveys. The manual mentions them, as does the National Safety Council report [39], and an almost contemporary report, *Speed regulation and control on rural highways. Report of a special investigation*, published by the Highway Research Board in 1940 [40].

Speed measurements were made since at least the mid-1920s to evaluate measures taken in "various States to regulate and control the speeds of motor vehicles on rural highways in the interests of safety to vehicles and pedestrians" ([40, p. 5]).

For the most part, means to measure speed "of an observed vehicle are based upon the determination of the time the vehicle takes in traversing a known distance" ([40, p. 77]). Various bodies had come up with devices, like the Eno Foundation (the aforementioned Enoscope, widely used), the Public Roads Administration (contact strips), but these only allowed to measure speed over a rather long distance, and for light traffic.

Electric-based deviced were also devised and allowed "to measure accurately small intervals of time" ([40, p. 78]). Longer distance speed have also been measured through licence plates identification or two-way radio contact.

2.3.1.3 Speed and delay

The manual refers to *speed and delay studies* as "a classification of how time is spent by the average vehicle in traffic, and the determination of the amounts of time consumed by each category" ([34, p. 72]). These surveys aimed at finding "the amounts, causes, locations, durations, and frequencies of delays" and therefore "overall, average running, and similar speed values".

Methods mentioned are the Floating Car, the Elevated Observer, and the License Check techniques:

Floating Car "floating" referring to "an attempt to assume the modal route speed through the general rule of passing as many vehicles as pass the test car" ([34, p. 73]). Various recording means could be set up during the trip, either with a manual log by the observer, or semi-mechanical as mechanical recorders available on the market at the time "graphically record[ed] a log of the relationship of vehicle speed and delay with regard to time" ([34, p. 73]). The latter is mentioned as "far superior to the other methods".

Elevated Observer which has people standing at places overlooking road segments "pick typical vehicles at random and record the pertinent data regarding their progress" ([34, p. 73]) through the selected segments.

License Check which "sacrifices accuracy in the movements of any one vehicle to base its results on those of a sample group" ([34, p. 73]). The method shortfalls are numerous according to the manual: over-all and running speeds can only be determined between observation points, the recorded delay is not documented (voluntary or caused by traffic), the "man hours required in recapitulation processes" ([34, p. 73]), and causes of delays remain unknown.

2.3.1.4 Origin and destination

Origin and destination studies generally aim at "determin[ing] location of the sources, termini, routes and relative importance of traffic movement" ([34, p. 75]). Several methods are documented by the manual:

Direct interview the simplest one, "widely used" ([34, p. 75]), "the only method of getting routes reasonably accurately" ([34, p. 75]). It "consists in stopping vehicles and asking the driver where he came from and where is going for the specific trip" ([34, p. 75]).

License plates either 1. through recording license plates of parked cars in an area and then inferring their destination from the vehicles registry list, 2. through recording at specific stations, on a card "the last three or four digits of the license number of each passing vehicle" ([34, p. 75]), a new card being used each minute or so. The method is said to be "adapted to locations where traffic is too heavy to be stopped for questioning" ([34, p. 76]), and motorists are unaware of the operation, thus reducing possible bias. The man-power required nonetheless seem to disqualify it for large perimeters.

Post cards which are "handed out to drivers as they pass the station" ([34, p. 76]), and then "are to be filled out by the driver and placed in the mail" ([34, p. 76]). Traffic must be slow so that cards can be handed out, like at a toll gate.

Tag on a car as "a pre-coded card is handed to the river or fastened to his vehicle as it enters the area under study" ([34, p. 76]), and the card is removed when the vehicle leaves the area. This method is apparently directed towards bypass studies "by assuming that any vehicle taking less than one and one-half times as long as the average minimum time required to traverse the area is a through vehicle" ([34, p. 76]).

The general sample rate below which any study is considered void is 10%.

2.3.1.5 Subsequent editions

The manual's second edition, in 1950 [41], by both the Institute of Traffic Engineers and the Association of Casualty and Surety Companies, was issued for "sound traffic engineering principles as a means of bettering traffic conditions".

Volume studies, titled "Motor vehicle volume studies" ([41, p. 138]), accounts for automatic recorders, which seemingly were not available on the market in 1941, for the manual's first edition. The two mainstream technologies of the early 1950s were photoelectric cells (lightbeam across the roadway, broken by the passage of a vehicle) and magnetic detectors.

Origin and destinations studies get a fifth method, the *home interview*, the "most comprehensive type of O-D study, obtaining information on all forms of trips (public transit, private vehicle, etc.)." ([41, p. 148]). Supplementing the home interview proper, complementary cordon inquiry is carried out with "a sampling of vehicles entering and leaving the area" ([41, p. 148]), and vehicular counts are recorded at specific stations.

Spot speed study, or "Motor Vehicle Speed Study" ([34, p. 152]), also gets additional methods, the most important being the radar meter. The *average speed* is described as "arithmetic average of a series of miles per hour values" ([34, p. 155]).

The Institute continued to regularly update the series, and its latest, seventh edition went out in 2016 [42].

2.3.2 The *Highway Capacity Manual* (HCM)

The first two editions of the *Highway Capacity Manual*, in 1950 and 1965, capitalize on the rapidly evolving research and theorization work of the 1950s and 1960s.

2.3.2.1 1950: the HCM's first edition

The flagship among the manuals of the period is without doubt the *Highway Capacity Manual* [35], whose first edition went out in 1950. It was published by the Committee on Highway Capacity, part of the Highway Research Board, and established in 1944. As reported by Kittelson [44], the inception of the manual was triggered by President F.D. Roosevelt's 1941 appointment of a committee in charge of designing a country-wide interregional highway system, which a decade later became known as the Interstate highway program. O.K. Normann, an engineer involved in multiple traffic observations studies since the 1930s [45], was a member of that committee, and took charge, in 1944, as chairman of the Committee on Highway Capacity.

In this context of post-war massive highway building schemes, engineers capitalized on the previous studies that held a more "local" or "occasional" approach, but were also seeking some standardization. The Foreword of the manual itself underlines the need of setting up "a rational and practical method for the determination of highway capacity", both for new highways ("the sound economic and functional design of new highways" ([35, p. iii])) but also for the adaptation of the existing network ("the adaptation to present or future needs of the many existing roads and streets" ([35, p. iii])). The variety of practices also translated in a variety of definitions for traffic engineering terminology, and beyond the capacity, the manual aimed at standardizing them: "the confusion that has existed concerning the meaning and shades of meaning of many terms used in traffic engineering practice has contributed [...] to the wide differences of opinion regarding the capacity of various highway facilities" ([35, p. 5]).

The manual fundamentally relies on the concept of *capacity*, an infrastructure related variable (the "supply" of the highway to the "demand" of traffic), which became the basis of all traffic-related policies and developments. The original observations and definitions made since the 1920s yielded a three-category approach. It stands as a compromise between an operational world which had been, for the past two decades, building a variety of rules-of-thumb, and the requirements of providing, through the manual, a sound theoretical background for the upcoming traffic-related operations: "the definitions given here are intended to be the most descriptive and most widely used in engineering practice" ([35, p. 5]). Nonetheless the authors still admitted things could change, and that what they proposed could be challenged by others, and was for a part a "compromise" ([35, p. 5]).

Capacity itself is described as "the term which is perhaps most widely misunderstood and improperly used" ([35, p. 5]). A fundamental figure for highway-design was thus subject to strong variations depending on where a traffic survey was conducted and who was in charge of it. The operational questioning behind the term is perhaps quite elementary: "how many cars can my highway cater for? how many cars will my highway cater for? how many cars my highway needs to cater for?"

The manual reasoning regarding capacity is a two-phase process. The first phase is referred to as the *prevailing conditions* which will alter the highway response to traffic. These conditions are classified into two groups:

the prevailing roadway conditions which "are determined by the physical features of the roadway" ([35, p. 6]), which are not subject to change; "unless some construction or reconstruction work is performed" ([35, p. 6])

the prevailing traffic conditions which "are dependent upon the traffic using the roadway" ([35, p. 6]), hence subject to quick variations (much quicker than the roadway).

Within this context, the manual defines three capacities:

the basic capacity is "the maximum number of passenger cars that can pass a given point on a lane or roadway during one hour under the most nearly ideal roadway and traffic conditions which can possibly be attained" ([35, p. 6]).

the possible capacity is "the maximum number of vehicles that can pass a given point on a lane or roadway during one hour, under the prevailing roadway and traffic conditions" ([35, p. 6])

the practical capacity is "the maximum number of vehicles that can pass a given point on a roadway or in a designated lane during one hour without the traffic density being so great as to cause unreasonable delay, hazard, or restriction to the drivers' freedom to maneuver under the prevailing roadway and traffic conditions." ([35, pp. 7–8]) The latter holds a very operational view. It relies on the freedom of the driver: behind this, the idea that the traffic engineer should do everything he can to allow this freedom of the driver to happen. The authors relate the practical capacity with the design capacity: "the highway has a design capacity during the planning stage, and a practical capacity after it is constructed" ([35, p. 8]).

As for the data used throughout the study, it still stands on a per-vehicle (we would now say "microscopic") approach, as stated in the "Basis of This Report" section: "vital information [...] can now be obtained for each individual driver, regardless of what the total traffic volume may be" ([35, p. 4]). Of course, technical devices such as those devised by Greenshields, but also by Normann himself (a graphic recorder), essentially yielded observations made at a given spot or over very short highway segments.

The capacity triggers the need for specific definitions for the rest of the traffic engineering field: roadway definitions, traffic control devices definitions, traffic and traffic operations definitions, land usage and development definitions. For our concern here, traffic operation definitions includes all variables previously observed: speed, delay, headway, volume, density:

speed is defined as "the rate of movement of traffic, or of specified components of traffic, expressed in miles per hour" ([35, p. 17]). The distinction is explicitly made between traffic and components of it (vehicles, for instance). Speed holds several sub-definitions.

The "average speed", "the average of the speeds of all vehicles at a specified point on a given roadway, during a specified period of time" ([35, p. 17]), clarifies the notion but does not describe the type of average used (arithmetic or harmonic).

For a highway segment, an "over-all speed" and an "average over-all speed" ([35, p. 17]) are defined; they recall previous definitions and observations made in the 1930s with license plate manual identification. The "over-all speed" is defined as "the total distance traversed, divided by the total time required, including all traffic delays, expressed in miles per hour" ([35, p. 17]). The "average over-all speed" is "the average of the over-all speeds of all vehicles on a given roadway during a specified period of time" ([35, p. 17]). In other words, the over-all speed is the reciprocal of the travel-time for a journey over a given route, and can also be called journey speed. Likewise, the average over-all speed can also be called the average journey speed.

The capacity allows the definitions of speeds related to the highway facility: the "critical speed" or "optimum speed", "the average speed at which traffic must move when the volume is at a maximum on a given roadway" ([35, p. 17]). Here, the speed is a parameter of the highway and seen as a consequence of the observed flow. The "design speed" and "operating speeds" are closely related, the first being "selected for purposes of design" ([35, p. 17]), and the second being the "highest over-all speed exclusive of stops at which a driver *can* travel on a given highway under prevailing conditions without at any time exceeding the design speed" ([35, p. 17]). Again, capacity is the major underlying idea: the reader obviously related the operating speed with the practical capacity of the highway.

delay quantifies, in terms of time, the lack of freedom the driver may have to suffer during his journey. The authors define it as "the time consumed while traffic or a specified component of traffic is impeded in its movement by some element over which it has no control. Usually expressed in seconds per vehicle" ([35, p. 17]). Impeding is a strong word, opposed to the freedom of movement. Although the driver has, or at least should, have control of his machine, there are events on which he has no control and which inflict him delays. Two types of delays are defined, "fixed delays", caused by the highway or traffic control devices in case of "light traffic volumes or low densities" ([35, p. 17]), and "operational delays", "caused by the interference between components of traffic" ([35, p. 17]). This clearly states that traffic itself inflicts delay to its components: the freedom of movement of each driver is impeded by its neighbors...

headway is defined as "the interval of time between individual vehicles moving in the same lane measured from head to head as they pass a given point" ([35, pp. 17–18]). Observed from a point on the side of the road, the headway, being a quite straightforward quantity, has been clearly defined since its first observations. The only point of debate was which part of the two succeeding vehicles was to be taken: head and tail, tail to tail, head to head.

volume is "the number of vehicles moving in a specified direction or directions on a given lane or roadway that pass a given point during a specific period of time" ([35, p. 18]). The volume was sometimes designated as the density, like by GREENSHIELDS in his "A Study of Traffic Capacity," with the units being the only way to discriminate it from the spatial density.

density is "the number of vehicles occupying a unit length of the moving lanes of a roadway at a given instant" ([35, p. 18]). The density therefore is a photograph of the given section of roadway at a given instant. The "average density" is "the average number of vehicles per unit length of roadway over a specific period of time" ([35, p. 18]). It can be reformulated as the average of successive pictures of the roadway.

Much like for the "critical speed", capacity defines the "critical density", "the density of traffic when the volume is at the possible capacity on a given roadway" ([35, p. 18]). The critical density is, like the critical speed, a highway parameter. Referring to the possible density means that the critical density will be dependent of the *prevailing conditions* both of the road and of the traffic, hence hold a variability. It is the tipping point in the volume trend: "at a density either greater or less than the critical density the volume of traffic will be decreased" ([35, p. 18]). The manual adds: "critical density occurs when all vehicles are moving at or about the optimum speed" ([35, pp. 18–19]).

Among the definitions, speed, volume and density show their close relationship between each other and with the capacity. Their intertwined dependencies is illustrated by the successive definitions of what is now known as the "critical point" under specific traffic and roadway conditions (in the manual's terminology, the "possible capacity"). On the one hand, the "optimum speed" is "the average speed at which traffic must move when the volume is at a maximum on a given roadway" ([35, p. 17]): the optimum speed is a consequence of the maximum volume. On the other hand, the *critical density* occurs "when the volume is at the possible capacity on a given roadway" ([35, p. 18]). Again, the volume triggers the density. The loop is closed by the relationship between critical density and optimum speed: "critical density occurs when all vehicles are moving at or about the optimum speed" ([35, pp. 18–19]).

Speed, density and volume being precisely defined, the relationship that link them by pairs (speed-volume, speed-density, volume-density), already investigated since the 1920s as reported here, gradually became the cornerstone of traffic engineering. In the manual, it is presented within the "Fundamentals of Highway Capacity".

2.3.2.2 1965: the HCM's second edition

The *Highway Capacity Manual* was subsequently updated, generally with around a decade between each publication. The second update [43], in 1965, drastically increased the size of the volume (from barely 140 pages in the 1950 edition, to more than 400!) as more cases were considered, perhaps under growing traffic-related issues, an expanding expressway network (the Interstate program had been launched a few years earlier), new means to measure traffic, and computers becoming available (although, for that latter point, given the limited availability of such machines, the methods and solutions proposed by the manual were to be compatible with a purely manual treatment). Between 1950 and 1965, much work had been done in theorizing, but also observing, the volume-speed-density relationships. Making an explicit use of it much more than in the 1950 edition, the 1965 edition introduced jointly with capacity, the levels of service, the milestone of this edition.

The 1950 definition for speed is expanded, reproducing the advances made since 1950, and published by various authors. Among the various speeds considered, definitions are given depending on how the average is done:

spot speed, not defined in [35], is "the speed of a vehicle as it passes a specified point on a roadway" ([43, p. 15]).

average spot speed (or time mean speed), designated as "average speed" in [35], is "the average of the individual spot speeds of all vehicles or a specified class of vehicles at a specific point on a given roadway during a specified period of time" ([43, p. 15]).

overall travel speed, referred to as the "over-all speed" in [35], keeps the same definition.

average overall travel speed , referred to as the "average over-all speed" in [35], gets a more precise definition: it is "the summation of distances traveled by all vehicles or a specified class of vehicles over a given section of highway during a specified period of time, divided by the summation of overall travel times" ([43, p. 15]). Its relationship with the journey time is this way clearly stated.

space mean speed , not defined in [35], is "the average of the speeds of vehicles within a given space or section of roadway at a given instant" ([43, p. 15]). Another definition is provided, relatively to the average travel-time on a route: "the average speed of a specified group of vehicles based on their average travel time over a section of roadway" ([43, p. 15]). The space mean speed is the journey or travel speed.

design speed shortens the definition found in [35]: "a speed selected for purposes of design and correlation of those features of a highway [...] upon which the safe operation of vehicles is dependent" ([43, p. 15]). The part that followed in [35], "the highest continuous speed at which individual vehicles can travel with safety upon a highway when weather conditions are favorable, traffic density is low, and the design features of the highway are the governing conditions for safety" ([35, p. 17]) has been removed, perhaps because of some redundancy with the highway design phase: its design speed is the one at which vehicles can travel outside of any disturbance.

operating speed holds the same definition as in [35], with only a small but meaningful modification: "the highest overall speed at which a driver can travel on a given highway under favorable weather conditions and under prevailing traffic conditions without at any time exceeding the safe speed as determined by the design speed on a section-by-section basis" ([43, pp. 15–16]). The operating speed therefore includes the notion of safety, and not only design.

free-flow operating speed, not defined in [35], is "the operating speed of a passenger car over a section of highway during extremely low traffic densities".

running speed , not defined in [35], is "the speed over a specified section of highway, being the distance divided by running time" ([43, p. 16]). The "running time", also not defined in [35], is "the time the vehicle is in motion" ([43, p. 16]). As to avoid improper averaging, the manual specifies that the running speed "average for all traffic, or a component thereof, is the summation of distance divided by the summation of running times" ([43, p. 16]).

The manual introduces the definition of "rate of flow", as the "hourly representation of the number of vehicles that pass over a given section of a lane or a roadway for some period less than one hour" ([43, p. 16]). This probably followed the development of automatic roadside traffic count units, that resulted in various measurement campaigns which, for the sake of comparison, should hold the same base unit (vehicles per hour, even if counts were realized on shorter time slots).

The distinction is also made between "interrupted flow" and "uninterrupted flow", concepts already used in the 1950 edition but not precisely defined. Interrupted flow is "a condition in which a vehicle traversing a section of a lane or a roadway is required to stop by a cause outside the traffic stream" ([43, pp. 16–17]), like a traffic light or signs, but not "causes internal to the traffic stream" ([43, p. 17]). Uninterrupted flow, for which most of the manual's theory is developed, is "a condition in which a vehicle traversing a section of a lane or a roadway is not required to stop by any cause external to the traffic streams although vehicles may be stopped by causes internal to the traffic stream" ([43, p. 17]).

Much of the theory that follows is dedicated to uninterrupted flow, as "few broad criterias can be described for interrupted flow" ([43, p. 77]). The definition of a level of service relies on two notions:

1. the "v/c ratio", with v being either the demand volume or the service volume "depending on the circumstances in which it is used" ([43, p. 79]), c the capacity; 2. the travel speed, as previously defined.

Levels of service are defined for different "types of facilities: 1. freeways and other expressways 2. other multilane highways 3. two- and three-lane highways 4. urban arterial streets 5. downtown streets (approximate only) " ([43, p. 80])

Uninterrupted flow assumption thus relies on the expressway network or rural highways, the urban environment being nonetheless somehow considered but with a watered down version of the analysis.

Seven levels of service are defined against a curve of operating speed function of volume to capacity ratio, labeled from A to F.

One can therefore say that by 1965, fundamental definitions of traffic were in place. Capacity was still subject of debates and extended definitions in the subsequent updates of the manual, but the basic ideas had been set up.

2.3.3 The Bureau of Highway Traffic's 1955 manual: *Traffic engineering*

The Bureau of Highway Traffic, at first part of Harvard University when it was created in 1926, was from 1938 transferred to Yale University, where it provided courses in traffic engineering. In 1955, the Bureau published *Traffic engineering* [36], as a manual "conform[ing] with the courses of study in the Bureau" ([36, p. v]), whose "basic purpose [...] was to provide a text for traffic engineering training and a reference for those engaged in highway traffic planning, operations and administration" ([36, p. v]). The book introduces traffic engineering as an answer to the "losses which waste community resources" ([36, p. 1]): the "phenomenal growth in highway traffic has brought serious amounts of loss through congestion and casualty" ([36, p. 1]).

The "nature of highway-traffic problems", as the authors put it, is "concerned with the achievement of a more efficient system of highway transportation" ([36, p. 2]) and "the conservation of community resources" ([36, p. 2]). More specifically, "traffic engineering" ([36, p. 3]) is "that branch of engineering which is devoted to the study and improvement of the traffic performance of road networks and terminals" ([36, p. 3]), whose "purpose is to achieve efficient, free, and rapid flow of traffic" ([36, p. 3]) while "at the same time, to prevent traffic accidents and casualties" ([36, p. 3]).

The essential traffic variables stem from the "discrete unit of traffic" ([36, p. 3]) made of "the man and his machine" ([36, p. 3]). The authors then identify the variables when describing traffic: "the primary characteristics of traffic movement, then, are concerned with *speed* (and delay), *volume* or time rates of flow, and *origin and destination* or the location, distance and direction of movement" ([36, p. 3]). The cited variables have, as already stated, been observed since the first traffic studies. Speed is associated with delay: in other words, this illustrates the conflict between the speed at which a unit of traffic wants to move, and the speed at which it is forced to move due to congestion, the inflicted time difference being the delay.

The analogy between traffic with the fluid theory, then at its beginnings at least in terms of theorization, can also be felt: "the secondary phenomena of *stream flow* and *intersection flow* establish capacity and other performance values of traffic facilities" ([36, pp. 3–4]). Under its first section, "Characteristics", the manual aims at giving background and definitions of the mentioned variables: after a chapter dedicated to the road user and one to the vehicle, plain chapters are dedicated to speed, then to volume, and to origin and destination. This is perhaps one of the first books, with the *Highway Capacity Manual*, to explicitly dedicate sections to traffic variables, as to their definition and how they can be measured.

In its approach and content, the manual is close to its Institute of Traffic Engineers counterpart, whose second edition predated it by five years.

2.3.3.1 Definitions of speed

The "Speed" ([36, pp. 45–66]) chapter defines several speeds, and proposes a "classification of speed values" ([36, p. 47]), as a "given vehicle [...] may actually be temporarily at a standstill, yet will accomplish a known distance in a known time which yields a particular speed value" ([36, p. 47]).

Several speeds, and associated methods of measurement, are detailed, much like in the aforementioned *Highway Capacity Manual* [35]. These include spot-speed, running speed and over-all speed:

spot speed is "the instantaneous speed of a vehicle at a specified location" ([36, p. 47]). Its measure methods are described as follows: "most methods of spot-speed study depend on measuring the duration of time a vehicle requires to traverse a known, relatively short distance, usually less than 200 ft" ([36, p. 48]), that is 60 m. This somehow contradicts the instantaneous definition often associated with spot-speed. The measuring devices themselves are described: the oldest are the mirror scope (or Eno-scope) and pressure-contact strips. Measuring speed by radar, which was devised in the 1940s, offers automatic records over much shorter distances, which other methods didn't necessarily permit. Time-lapse photography is also mentioned, as devised by Greenshields in the 1930s.

Spot speed is the foundation of many traffic studies, and various techniques are described in the subsequent pages. However, they should not be the only way to study traffic dynamics, as "though spot-speed studies are well suited to measuring the fluctuations in speed at a given point throughout a period of time, they are unsatisfactory in obtaining the fluctuation in speed or the delay incurred by the movement of traffic throughout the length of a given route".

running speed is "the average speed maintained by a vehicle over a given course while the vehicle is in motion" ([36, p. 47]).

over-all speed is "the effective speed with which a vehicle traverses a given route between two terminals" ([36, p. 47]). Both running speed and over-all speed are used in what the manual calls "speed and delay studies", which, by obtaining these speeds, show "with varying degrees of accuracy, the amount, location, duration, frequency, and causes of delay in the traffic stream" ([36, p. 62]) and "the amount of time spent in actual motion from point to point along a given route" ([36, p. 62]). The manual describes three collection methods: floating car, elevated observer and license plate:

The "floating car" method is "a vehicle driven over a given course of travel with every effort to 'float' ([36, p. 62]) with the traffic stream" ([36, p. 62]). Doing so, "it will approximate the average rate of speed which exists on the route" ([36, p. 62]). A refinement is when the "test vehicle overtakes as many vehicles as the test vehicle is passed by" ([36, p. 62]), thus, "with sufficient number of runs, approach[ing] the median speed of the traffic movement on the route" ([36, p. 62]). During the run, one or two observer may record various variables, such as speedometer, mileage, events, etc. The method was empirically and mathematically assessed by Wardrop and Charlesworth in 1954 [46]: the authors concluded that "the method is efficient and practical, and is particularly suitable when a general picture of traffic conditions on a network of streets is required" ([46, p. 158]). This once shows how close traffic research was close to operational issues.

The "elevated observer" method works by "stationing observers in [...] elevated points from which a considerable length of route may be observed" ([36, p. 62]). By "selecting vehicles at random" ([36, p. 62]), the observers "record time, location and cause-of-delay information" ([36, p. 62]), as they would aboard a floating car. The method is nonetheless described as difficult to implement due to the difficulty of "secur[ing] suitatble points for observation throughout the length of the route to be studied" ([36, p. 62]).

The "license plate" method involves "investigators stationed at control points along the route enter[ing], on a time-control basis, the license-plate numbers of passing vehicles." ([36, p. 63]) It is described as "satisfactorily employed [...] when the amount of turning off and on the route is not great and only over-all speed values are to be secured." ([36, p. 63]) Despite its exhaustivity in terms of over-all speed, with the means of the time, "careful and time-consuming office work" ([36, p. 63]) is required.

These studies yielded, among other things, time-zone maps (isochrones from a specific location), frequency, causes and duration of delay.

These definitions correspond to those of the 1950 *Highway Capacity Manual* [35].

2.3.3.2 The traffic volume

The "Volume" ([36, pp. 67–89]) chapter refers to the "counting the number of traffic units passing a given point or collecting [the number of traffic units] in a given area during a known period" ([36, p. 67]), which yields a "*time rate* of flow" ([36, p. 67]). Traffic volume, as shown before, is "commonly employed in operation, design, and planning" ([36, p. 67]) but also "extreme significance in dealing with practical problems" ([36, p. 67]). The manual mentions the volume counting techniques available at the time, either manually (through hand tally or manually operated counters) or automatically (through automatic counters). Automatic counters mentioned are:

light beam through the "interruption of a light beam falling on a photoelectric cell as traffic passes" ([36, p. 68]).

treadle through the "mechanical actuation by passage of vehciles over a treadle which closes an electric circuit directly" ([36, p. 68]).

pneumatic through the "pneumatic action on an air switch attached to a flexible tube over which traffic passes" ([36, p. 68]).

magnetic detectors which are today's traffic loops.

A key point of counting, the aggregation periods, is also discussed by the manual. As new automatic counting technologies became available, the choice of the aggregation time period became a concern. The matter here is to find a balance between "extremely short counting period, such as 1 or 2 min of flow [that yield] usually an unwarranted amount of numerical details" ([36, p. 68]), and "daily totals [with which] there is frequently insufficient detail to lend the data for analytical purposes" ([36, p. 68]). The conclusion was that "the purpose of study and the rate of fluctuation in the traffic stream form the basis for determination of the duration of the elementary counting period" ([36, p. 68]).

The chapter considers other aspects of traffic volume measurement: counting locations, magnitudes of traffic volume, composition of traffic volumes, cyclical variations (daily, weekly, seasonal time patterns), distribution of annual traffic volumes by day and hour. These aspects are well known of today, but were not so clear when the manual was written.

The chapter's approach on the short count technique, already described in the Institute of Traffic Engineers' manual, underlines that traffic data has a cost, even when considering its simplest form (volume): "because of the cost of collecting volume data, there have been developed various methods of *short counts* for determining the entire pattern of traffic stream" ([36, p. 85]). The method relies on "the consistency of traffic fluctuation patterns" ([36, p. 85])). In other words, this was the sampling issue: how to design a traffic count campaign that will be relevant for long-term operational decisions, such as road building or improvement?

The chapter closes on two short paragraphs, that are worth mentioning as they present issues that are still very important: induced traffic ("a new traffic facility, such as a bridge or non-stop route in urban areas, usually induces traffic volumes which cannot be accounted for on the basis of cyclical variations or trends, [...] especially in urban areas and under conditions where the facility creates a new accessibility between areas" ([36, p. 87])) and long-time trends in traffic volumes ("trends in vehicle registration and gasoline consumption are frequently applied in estimating future traffic flow" ([36, p. 88])).

2.3.3.3 The origin and destination of traffic

The "Origin and destination" ([36, pp. 90–122]) chapter provides collection techniques and analysis for origin-destination studies, along with ensuring oneself of proper sampling as not all vehicles may be tracked. Such studies are essential for the traffic engineer as they "determine the direction of travel, selection of route, and length of trip" ([36, p. 90]) of the sampled fleet. Several methods are described by the manual, and they offer a well-documented insight on the American methods available at the time. They all implied manpower to collect the data, and later analyze it.

The "license plate", "post card" and "route interview" methods are described, in the line of the Institute of Traffic Engineers' manual. The novelty is the "home interview", which was set up by the Federal administration, through a joint work of the Bureau of Public Roads and the Bureau of the Census. The manual refers to the home interview manual published by the Federal administration, *Manual of procedures for the metropolitan area traffic studies*, originally distributed in 1944 and published in a revised form in 1946 [47]. The "Scope and Objectives" introductory section of the home interview manual helps understanding the motivations behind devising a traffic survey technique. The growing traffic congestion in cities ("Today, it is in and near the large cities that traffic is delayed and inconvenienced by congestion" ([47, p. 1])) stands as the primary concern. Traffic surveys had already been carried out since several decades, but the classic "analysis of traffic flow for specific locations is not adequate for the development of a comprehensive city transportation system" ([47, p. 2]). They do not allow to identify routes taken by motorists to get to their destination. "Only through the comprehensive knowledge of origins and destinations of people and materials can authorities be certain as to the correct location and adequacy of [new highway] improvements" ([47, p. 2]). The method relies on controlled sampling procedures, as it was clearly understood that all traffic clearly could not be measured. Recall that a decade earlier, the fact that a study could not catch all traffic meant it was highly questionable.

The manual then goes through planning procedure of an O-D study, and the analysis of its results. This important chapter shows how traffic data played a crucial role in understanding the dynamics of the country, and how classic spot measures were very early complemented by much more exhaustive measurement.

The "Stream Characteristics" ([36, pp. 123–147]) chapter recalls, by its title, the fluid dynamics analogy with traffic. The "Longitudinal Distribution of Vehicles" section introduces time and space gaps between vehicles. The "Natural Distribution of the Traffic Stream" introduces Poisson theory, as "knowledge of the natural longitudinal distribution of vehicles in the traffic stream can be most useful in predicting the characteristics of flow and stream action" ([36, p. 133]).

2.3.4 *Statistics with applications to highway traffic analyses*

Another main contribution to the field of traffic manuals, and by the way one of Greenshields' last operational milestones, is the *Statistics with applications to highway traffic analyses* manual [37], co-written by Greenshields and Weida. The manual compiles statistical theory and techniques, as stated in the "Preface" ([37, pp. v–vi]), "to assist the engineer in determining the type and amount of data he needs to obtain sufficiently accurate answers to his problems and save him time and effort" ([37, pp. v–vi]).

The first chapter, "The nature and utility of statistics" ([37, pp. 1–11]), documents the mood of time regarding the encounter of statistics and traffic. The authors state: "there is clearly a need for increased knowledge of traffic behavior in order that traffic regulation and planning may be made more scientific. The method by which scientific knowledge is increased is to observe what happens and then by inductive reasoning to establish general laws pertaining to these happenings. It is the purpose of this book to develop a scientific system known as *Statistical Methods* and show how to use these methods for analyzing and solving traffic problems" ([37, p. 1]).

This statement underlines the growing necessity, in the postwar period, for a structured theory and guidelines to engineers, which could be somehow found in the various papers published since the 1920s (for instance, in the "Highway Research Board Proceedings" series) but with no clear overview.

Still in the first chapter, where the book's plan is layed out, Greenshields offers a glimpse of the difficulty to collect traffic data. The paragraph, "Means of Measuring the Variable, and Precautions to be taken" ([37, pp. 6–7]), recalls past experiments: "it has been found by experience that it is sometimes necessary to design and construct special equipment or appratus to record field data". The author mentions two specific equipments, that fed the major studies of the 1930s: the time-motion picture, in 1932, used "only after considerable thought", and the Enoscope, to record the speed, "not infaillible".

The book itself is designed for the analysis of collected datasets: chapters II to IV, that follow the introductory one, are dedicated to the statistical theory and its links with the observation of traffic, and are meant to provide the necessary statistical background to the engineer.

The final chapter, "Some applications of statistical methods" ([37, pp. 150–214]), deals with operational use of the statistical theory for the engineer. Even today, some of the points made are still very valuable, and they offer a great testimony of the traffic engineers spirit at the time. Highway capacity is presented as the "primary concern" ([37, p. 150]), as it is "connected with the main purpose of a highway which is to serve traffic". Capacity theorizes the operational philosophy that a road must help as much traffic as possible while minimizing congestion. These ideas, not necessarily explicitly formulated, had been motivating many of the studies since the 1920s.

All the manuals shared the common goal of offering a comprehensive review of existing principles and practices regarding traffic engineering. They concentrate on operational variables, for which we can already perceive two overlapping categories. The first category includes variables relative to the traffic stream or traffic flow, with the speed, the volume, the density, and an associated highway facility related parameter, the capacity. The second category covers the network performance or efficiency, with the travel-time (and its associated journey speed or over-all speed) and the volume considered within origin-destination studies.

Beyond the definitions these manuals provide, they also offer insight on the methodologies available at the time, but also on the motivations standing behind this whole branch of engineering. These include maintenance, safety, congestion which is seen as something meant to be overcome, and the performance of the network, through its efficiency.

Sign of their usefulness, the stability of these publications is worth noting, as most of these books have been repeatedly updated until today.

2.4 Towards modern definition of traffic flow variables

While various organizations published their manuals, the traffic research community, formed by operational engineers, proceeded to precisely define a traffic flow terminology. This process took about a decade, from Wardrop's work in 1952 to Edie's and Haight's respective works in 1963. At last, in 1975, the Transportation Research Board, issued a special report, *Traffic Flow Theory. A Monograph* [50], summarizing twenty years of work on traffic flow, including the definitions of its variables.

In defining traffic flow variables, and their relationships, two questions arise: the question of scale (over which space and time perimeter are the variables defined?) and the question of averaging (space or time average?). These have remained an important point up until today.

2.4.1 Wardrop's 1952 "Some Theoretical Aspects of Road Traffic Research": the need for theory for a practical subject

Wardrop's 1952 paper, "Some Theoretical Aspects of Road Traffic Research" [28], is most famous for exposing a method of judging "the effect of some future improvement of a road system", whereas "some estimate must be made of the distribution of traffic on the various roads affected, including not only new roads but all existing roads from which traffic may be diverted" ([28, p. 344]). What has now become known as "Wardrop's principles" and is used in traffic assignment theory, is nonetheless not the only major point he made in this paper.

The early 1950s were a turning point, and definitions and practices were gradually being settled down, as various institutions published their manuals, the most known being the *Highway Capacity Manual* in 1950 [35]. These were the first major tentatives of establishing theoretical common grounds for traffic studies, and held strong operational purposes.

Wardrop thought that "it is not always appreciated that in a severely practical subject such as traffic engineering there is need for theory" ([28, p. 326]), and therefore wrote his article with, in mind, the need of a "theoretical background [...] if the observations are to be economical and useful and their interpretation valid" ([28, p. 326]).

Throughout his paper he made a point at defining the variables involved (flow, speed, journey time, ...), propose sound statistical treatments to answer operational questions (before-after studies, traffic surveys, etc.) both in collecting the results (sample size) and interpreting them (statistical tests, theoretical assumptions, analytical developments).

2.4.1.1 Formalized definitions for space-mean and time-mean speeds

In the matter of traffic variables on which we focus here, his paper defines the notion of "speed", within the section "Flow and speed of traffic" ([28, pp. 326–333]). There was an operational need for a theoretical description of traffic, which implies, for Wardrop, the knowledge, "at all times considered" ([28, p. 326]), of "the way in which vehicles are distributed along the road" ([28, p. 326]). This knowledge is provided by the Poisson theory, as inherited from Adams's work in 1936, to which Wardrop refers. Thus, the definitions are made in a stochastic context, in which each vehicle is considered independent of each other, and time-space positions of each vehicle are random variables. The definitions and distributions of speed stems from a statistical consideration of road traffic. Speed here is the variable that allows to know where vehicles will be in a later time.

Wardrop, supposing a traffic stream "composed of a number of subsidiary streams, in each of which all the vehicles are traveling at the same speed and form a random series" ([28, p. 327]), defines the distribution of speed in time, and the distribution of speed in space.

Following the author's reasoning[5], consider at first the traffic stream in respect to time, each

[5] For the sake of clarity, the author has not systematically indicated when he literally quoted Wardrop in this section. The original development may be found in [28, pp. 326–333].

subsidiary stream i has a flow q_i and a speed v_i. The total flow Q of the traffic stream is:

$$Q = \sum_{i=1}^{C} q_i \tag{2.4.1}$$

Then:

$$f_i = \frac{q_i}{Q} \tag{2.4.2}$$

is the frequency in time of vehicles traveling at speed v_i ; of course, $\sum_{i=1}^{C} f_i = 1$.

The distribution of speed in space stems from the time-wise distribution. Within the subsidiary stream i, with flow q_i and speed v_i, the time-interval between each of its vehicles is the inverse of flow $\frac{1}{q_i}$, and the distance traveled by each vehicle during this time-interval is $v_i \times \frac{1}{q_i}$. WARDROP thus defines the "concentration" or "density" k_i of the stream i, as "the number of vehicles per unit length of road at any instant":

$$k_i = \frac{1}{\frac{v_i}{q_i}} = \frac{q_i}{v_i} \tag{2.4.3}$$

The total concentration being:

$$K = \sum_{i=1}^{C} k_i \tag{2.4.4}$$

Then:

$$f'_i = \frac{k_i}{K} \tag{2.4.5}$$

is the frequency in space of vehicles traveling at speed v_i, with $\sum_{i=1}^{C} f'_i = 1$

The time distribution and space distribution each have a mean value:

- the time-mean speed is the mean of the time distribution of speed:

$$\overline{v_t} = \sum_{i=1}^{C} \frac{q_i}{Q} v_i = \sum_{i=1}^{C} f_i v_i \tag{2.4.6}$$

- the space-mean speed is the mean of the space distribution of speed:

$$\overline{v_s} = \sum_{i=1}^{C} \frac{k_i}{K} v_i = \sum_{i=1}^{C} f'_i v_i \tag{2.4.7}$$

From the space-mean speed, with $k_i \times v_i = q_i$, WARDROP derives the flow-concentration-speed relationship:

$$\begin{aligned} \overline{v_s} &= \sum_{i=1}^{C} \frac{k_i v_i}{K} \\ &= \frac{1}{K} \times \sum_{i=1}^{C} q_i \\ &= \frac{1}{K} \times Q \end{aligned} \tag{2.4.8}$$

Hence:

$$Q = K \times \overline{v_s} \tag{2.4.9}$$

noting that "there is no equivalent relation involving the time-mean speed" ([28, p. 330]).

WARDROP then seeks, from vehicular speeds v_i measured "at a point on the road" ([28, p. 331]), to obtain the corresponding time-mean and space-mean speeds. The point on the road is assimilated with a "short measured distance" ([28, p. 331]) L.

If timing each vehicle i across L, the time one vehicle takes to cross L is t_i, and its corresponding speed is $v_i = \frac{l}{t_i}$.

The arithmetic average $\overline{v} = \frac{1}{n}\sum_i v_i$ is the time-mean speed.

Now, if considering the average travel-time $\bar{t}$ across L, then $\bar{t} = \frac{1}{n}\sum t_i$. The average speed, hence the reciprocal of the mean travel-time by the distance, the space-mean speed:

$$\begin{aligned}\overline{v_s} &= \frac{l}{\bar{t}} \\ &= \frac{l}{\frac{1}{n}\sum t_i} \\ &= \frac{l}{\frac{1}{n}\sum \frac{l}{v_i}} \\ &= \frac{n}{\sum \frac{1}{v_i}}\end{aligned} \tag{2.4.10}$$

This demonstrated how to deduce space-mean speed from spot-speed measurements.

Moreover, Wardrop demonstrated what became a seminal relationship between space-mean and time-mean speed:

$$\overline{v_t} = \overline{v_s} + \frac{\sigma_s^2}{\overline{v_s}} \tag{2.4.11}$$

With σ_s^2 the variance of the space distribution of speed:

$$\sigma_s^2 = \sum_{i=1}^{C} \frac{k_i}{K}(v_i - \overline{v_s})^2 \tag{2.4.12}$$

The use of space or time-mean speed in a traffic study "is really one between speed and journey time" ([28, p. 331]), and when carrying out comparison, "it is most important that the same mean [...] be used throughout any investigations, so that all comparisons are fair" ([28, p. 331]), although "in a particular investigation, it may not be very important which of the two means is used" ([28, p. 331]).

Wardrop thus presents the difference between time-mean and space-mean speed not only on the grounds of the harmonic average relationship, but as two ways of assessing "the characteristics of successive journeys on a given route" ([28, p. 331]). The analysis "in terms of speed" ([28, p. 331]) yields the time-mean speed, whereas the analysis "in terms of time, giving the mean journey time, which by division into the length of the route" ([28, p. 331]), yields the space-mean speed.

Wardrop is well aware of the advantages of a journey time approach instead of speed approach, both for the user ("in planning a journey, one wishes to know how long it will take rather than what the average speed will be" ([28, p. 332])) and the engineer ("the cost of slow movement is measured in terms of time" ([28, p. 332])). Nonetheless, on a technical aspect, he argues that "speed measurement are frequently more consistent", as "journey times often have very skew distributions with a long 'tail' consisting of very slow journeys, whereas the corresponding distributions of speed tend to be more symmetrical" ([28, p. 333]). He assesses his stand by comparing the coefficient of variation of both journey time and speed distributions over a corridor, and thus identifies that less runs are required to identify the mean speed than to identify the mean journey time.

2.4.1.2 WARDROP's view of the flow-speed relationship

The relationship between flow and speed was more thoroughly investigated by WARDROP, through the notion of capacity in the paper section "Capacity of Road Systems" ([28, pp. 334–337]). He finds "more appropriate to regard the speed as a function of the flow than vice versa" ([28, p. 334]). The prevailing idea he reports was that speed decreased as flow increased, but that did not conform well with jammed traffic coming at a standstill, i.e. zero speed, and hence zero flow. WARDROP, like GREENSHIELDS nearly twenty years before, supposes a relationship between the running speed against the flow based on empirical data drawn from a selection of London's streets.

Unlike GREENSHIELDS', WARDROP's assumed formula holds a seemingly never-ending flow increase linked with a linear-trend decrease of speed. Despite the questionable analytical treatment, WARDROP defined *capacity* in a way that differed somewhat from contemporary work. Most research on the subject since the 1920s, and the flagship *Highway Capacity Manual*, adopted a roadside volume-based view of capacity, as the maximum number of vehicles that could be serviced by a highway in a given time. WARDROP, instead, adopted an user-perspective view, defining capacity as "the flow which produces the minimum acceptable journey speed" or, in other words, the maximum acceptable journey time.

2.4.1.3 Some theory for before-after studies

Another section of WARDROP relevant here is the "'Before-and-after studies'" ([28, pp. 348–353]). Before (x_i) and after (X_i) observations are assumed to be randomly chosen within the population, each independently of one another. WARDROP develops the analysis methodology between the two situations, as the comparison of the difference $d = \overline{X} - \overline{x}$ of the means $\overline{x}$ and $\overline{X}$ of both observations sets, $\overline{x} = \sum_{i=1}^{n} x_i$ and $\overline{X} = \sum_{i=1}^{n} X_i$.

WARDROP, after a discussion on the size of samples, then formalizes computations on two indicators still of use today: average journey characteristics (time, distance, and speed), and vehicle characteristics (vehicle-mileage and vehicle-hours).

2.4.1.4 WARDROP's work reception by his fellow engineers

His paper's good reception in the traffic engineering community can be hinted in the printed *Discussion* [51] that follows the paper. The relationship between theory and operational needs was at the center of the debates.

The need for theory is strongly supported, as reported by several discussants, among which GLANVILLE, who sees theory as a way to "cut down the man-power required in a research" ([51, p. 362]). Moreover, traffic research is part of a broader "growing interest in traffic problems", especially regarding "the provision of proper facilities for traffic played in national productivity" ([51, p. 363]), after a "too long [period during which] roads had been looked on as luxuries, which the country could ill afford" ([51, p. 363]). Engineers investigated theory as political concern for a proper road network was high. The concern of the required investment for any traffic studies was shared by other discussants, such as DUFF: "whilst rule-of-thumb methods would give results, the greatest economy and efficiency could be achieved only when proper attention was paid to the theory" ([51, p. 373]).

Another discussant, SMEED, underlines how "theoretical analysis [...] emphasized the importance of the difference between the two ways of calculating mean speed" ([51, p. 370]), as "every schoolboy was taught that such difference existed, but few people realized how great a difference could occur in practical cases" ([51, p. 370]).

The discussion of speed-flow relationship drew much debate.

First, the random characterization of traffic, as a series of independent event, was much questioned in a context that had evolved since ADAMS's observations fifteen years before. Free-flow traffic was not always the norm. In a free-flowing condition, with no interference (like an intersection), traffic was proved by ADAMS to follow a Poisson distribution in time, when viewed from the roadside. In his paper WARDROP proved that if vehicles were randomly distributed in time, they were also randomly distributed in space. In the discussion, ADAMS himself nonetheless warned that stating that "speeds of successive vehicles in space or in time form a sequence of random variables" ([51, p. 364]) relied on a definition of random that was not the one that prevailed in his work, in which random meant independence of events. The question was also asked as to when traffic resumed "randomness" downstream of an intersection.

The behavior of the speed-flow relationship beyond the capacity was also thoroughly debated. BENNETT interestingly questioned the reasons standing behind the observation "when there was larger flow, there was a lower speed" ([51, p. 365]). The major reason was safety, and that drivers drove slower when traffic increased. BENNETT then asked "if motorways were to be built [...], the safety factor would enter into the problem of design, and would offset economies"[6]. Beyond the absurdity of the statement to today's reader, it nonetheless shows strong links between traffic research and major infrastructure decisions, which had difficulties finding ground to justify the investment into the "unknown" (a car-dedicated infrastructure) whereas until then, most highway works were online upgrades of previous roads that kept their all-purpose designation.

On the speed-flow diagram, DUFF proposed a diagram that started at zero speed and zero flow, but also ended there: past a certain speed value, flow would keep decreasing until it reached zero. Besides the assumption of zero speed and zero flow for the free-flowing part of traffic ("when there was no vehicles the speed and flow would be zero" ([51, p. 374]), the general idea that "as an increasing number of vehicles wanted to enter the section, a point was reached where the flow was reduced to zero and there was a complete jam" ([51, p. 374]) still stands today. This had also been hinted by GREENSHIELDS. Nonetheless, DUFF's reasoning remained incomplete, and he himself felt "unconvinced" ([51, p. 374]), as he interpreted the progressive jamming past a certain speed as a need for a absurdely low speed limit: "on that theory; all that it was necessary to do was to introduce a speed limit of about 5 miles per hour, and then most of London's traffic problems would be solved" ([51, p. 374]).

2.4.2 The traffic stream model: LIGHTHILL and WHITHAM's 1955 "On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads"

The Lighthill-Whitham-Richards (LWR) model, developed independently by LIGHTHILL and WHITHAM [29, 30] and RICHARDS [52], and published in 1955-1956, is the theoretical cornerstone of traffic viewed as a "stream" or "flow" of "particles". The model stems from the way traffic was measured, as aggregates through time and/or space.

2.4.2.1 Establishing the equation system

LIGHTHILL and WHITHAM's work offers a comprehensive, general development of models that had been considered for the analysis of "flood movement in long rivers" ([29, p. 281]).

[6] Britain's first motorway, the Preston bypass, now part of the M6 motorway, opened in 1958.

Flood movements have been studied since the second half of the XIXth century, and progressive theorization had yielded some partial knowledge of wave theories, always in a fluid mechanics context.

The “kinematic wave theory” ([29, p. 288]) is considered for “one-dimensional flow systems” ([29, p. 282]), and relies on the assumption of a “functional relationship between: 1. the flow q (quantity passing a given point in unit time), 2. the concentration k (quantity per unit distance), 3. the position x. ” ([29, p. 282])

The equation of continuity, or conservation law, for the fluid taken over “a small element of length” ([29, p. 282]), is the following first-order differential equation:

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = 0 \tag{2.4.13}$$

In other words, the variation of the density of a small instant is equal to the difference between the inflow and the outflow.

Supposing the functional relationship between q, k and x:

$$q = q(k, x) \tag{2.4.14}$$

And setting c as:

$$c = \left(\frac{\partial q}{\partial k}\right)_x = c(k, x) \tag{2.4.15}$$

The equation of continuity then becomes:

$$\frac{\partial q}{\partial t} + c\frac{\partial q}{\partial x} = 0 \tag{2.4.16}$$

c is the velocity of waves with constant flow q:

$$\mathrm{d}x = c\mathrm{d}t \tag{2.4.17}$$

At a point x, the space-mean velocity v is the ratio of the flow q by the concentration k:

$$v = \frac{q}{v} \tag{2.4.18}$$

Then the wave velocity c as a function of v:

$$c = \frac{\mathrm{d}}{\mathrm{d}k}(vk) = v + k\frac{\mathrm{d}v}{\mathrm{d}k} \tag{2.4.19}$$

Which shows how the wave velocity c compares with the space-mean velocity v, depending on how k and v vary, and hence the sign of their differentials.

The wave velocity c itself depends on flow q, and thus different flows cause different wave speeds. Waves “may develop discontinuities, due to the overtaking of slower waves by faster one” ([29, p. 283]). The authors named them “shock waves, since their process of procession is exactly that of shock waves in a gas”.

The speed U of a shock wave is given by the law of conservation across the wave. We consider a stationary section of length L anchored to the shock front located at $x_U(t)$, with matter moving from $x = 0$ to $x = L$, containing n elements.

$$k(x,t) = \begin{cases} k_1 \text{ for } x \leqslant x_U(t) \\ k_2 \text{ for } x > x_U(t) \end{cases} \tag{2.4.20}$$

and a flow $q(x,t)$:

$$q(x,t) = \begin{cases} q_1 \text{ for } x \leqslant x_U(t) \text{ (inflow)} \\ q_2 \text{ for } x > x_U(t) \text{ (outflow)} \end{cases} \tag{2.4.21}$$

During a time $\mathrm{d}t$, the shock front moves by $\mathrm{d}x_U(t)$, and n varies of the difference between inflow and outflow, i.e. $\mathrm{d}n = (q_1 - q_2)\mathrm{d}t$.

n is a function of k, and $n = kL = k_1 x_U + k_2(L - x_U)$, so that its differential is:

$$\mathrm{d}n = k_1 \mathrm{d}x_U - k_2 \mathrm{d}x_U \tag{2.4.22}$$

Then:

$$\begin{aligned} U &= \frac{\mathrm{d}x_U}{\mathrm{d}t} \\ &= \frac{q_1 - q_2}{k_1 - k_2} \end{aligned} \tag{2.4.23}$$

Geometrically, for a given x, U is "the slope of the chord joining the points (k_1, q_1) and (k_2, q_2) on the flow-concentration diagram" ([29, p. 283]). The limit case, "when the shock wave becomes a continuous wave" ([29, p. 283]), the chord becomes a tangent to a point (k, q) and $U = c = \frac{\partial q}{\partial k}$.

Among the limits of the model, LIGHTHILL and WHITHAM warn about the flow-concentration relationship, "in which the flow is accurately a function of concentration and position" ([29, p. 283]), as "normally some small time lag may intervene between ajustments of flow and concentration at a given point." ([29, p. 283]). Therefore the model must be considered the description of "the development of flow with reasonable accuracy over times large with such a time lag, provided that the diffusive effects due to it, and to statistical deviation from the mean flow-concentration diagram, are small by comparison with the wave effect." ([29, p. 283]) The statistical validity of the assumed relationship requires some "depth" in time: the data observed must be averages, and not instantaneous values.

The flow-concentration relationship is dependent in x and k, but the simple case often supposes space invariability. In this simple case, when $q = q(k)$, then along a wave, since q is constant, then k is, and then c, i.e. a wave moves with constant velocity: "in a space-time diagram the waves are straight lines" ([29, p. 283]).

In case the flow q depends both on concentration k and space x, the wave velocity c can be expressed as a function of flow q and space x, $c = c(q, x)$, and the wave path in a space-time diagram is defined by integrating the velocity through x (with a a constant):

$$\begin{aligned} t &= \int_0^x \frac{\mathrm{d}x}{c(q,x)} + a \\ &= \int_0^x \left(\frac{\partial k}{\partial q}\right)_x + a \end{aligned} \tag{2.4.24}$$

2.4.2.2 Kinematic waves for traffic

The application of the kinematic wave theory to traffic was extensively developed by LIGHTHILL and WHITHAM in a second part [30] of their study, the first part [29] being dedicated to the study of floods.

As the title of second part suggests, "On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads," "the 'continuous-flow' approach represents the limiting behavior of a stochastic process for a large 'population' (total number of vehicles)" ([30, p. 318]), which implies the theory was originally meant to be applicable to "large-scale problems only–principally to the distribution of traffic along long, crowded roads" ([30, p. 318]). The question of scale is therefore key in the application of the kinematic wave theory, and the authors warned about this from the start.

The development on "The Flow-Concentration Curve" ([30, p. 319]) is itself facing the paradox of the definition of flow q and concentration k. On one hand, the authors concede that they "have no significance except as means" ([30, p. 319]), but also state that "the purpose of the [kinematic waves] theory is to ask how they vary in space and time", hence assimilating in some way average quantities with instantaneous ones. The key argument making the assumption "reasonable" ([30, p. 319]) is that "on a long crowded road [...] the means can be taken over relatively short distance or time intervals" ([30, p. 319]) compared with the scope of the model, which aims at "variations over much greater distances and times" ([30, p. 319]). The reader will note the lack of any precise quantification.

This also means that the assumed functional relationship between flow q and concentration k is one of means taken over these "relatively short" ([30, p. 319]) space or time sections, but that it also stands on long-term variations, hence that is stable through time and space.

Analytically, flow q and concentration k are defined at a location x and a time t, but both x and t represent respectively a spatial and time slice. The scale of these slices is vague. x is centered over a section spread "short distance dx" ([30, p. 319]).

The time-averages on this section dx are done for a time interval "of moderate length τ [...] long-enough for many vehicles to pass" ([30, pp. 319–320]). Once again, the scales are not precisely defined.

The definition of traffic flow q, where "n is the number of vehicles crossing the slice in time τ" ([30, p. 320]):

$$q = \frac{n}{\tau} \tag{2.4.25}$$

The concentration k is also defined for a small section dx, and defined as the ratio of the average number of vehicles $\frac{\mathrm{d}t}{\tau}$, by the section's length dx. Therefore concentration is seen as "the number of vehicles per unit length of road" ([30, p. 319]).

$$k = \frac{\frac{\sum \mathrm{d}t}{\tau}}{\mathrm{d}x} \tag{2.4.26}$$

Finally, the speed v is defined as WARDROP's space-mean speed, "both the ratio of flow to concentration" ([30, p. 319]) and "the ratio of length slice to average crossing times" ([30, p. 319]):

$$v = \frac{q}{k} = \frac{\mathrm{d}x}{\frac{1}{n}\sum \mathrm{d}t} \tag{2.4.27}$$

This is, in the line of WARDROP's work, a theorization of the spot observations of traffic.

The authors are well aware of the difficulty of observing k directly (outside of air survey campaigns).

LIGHTHILL and WHITHAM's intuitive introduction, by the moving observer, of the interpretation of the flow-density relationship as the result of waves through traffic remains, the author believes, the best way to introduce the concept.

An observer moving at uniform speed U records, during a period τ, the vehicles that pass him and the vehicles he passes, and in the end computes the difference $\Delta n(U)$. This difference is the number $q\tau$ of vehicles that would pass him if he were stationary ($U = 0$), minus the number $kU\tau$) of vehicles, at density k, over the distance $U\tau$ he traveled:

$$\Delta n(U) = (q - kU)\tau \tag{2.4.28}$$

Now, two observers moving at speed U, the second following the first one, while staying a time τ behind him. The flow q and concentration k change with time, but the first observer (and likewise, the second one, τ time units behind him) adapts his speed U "the number of vehicles which pass them, minus the number which they pass is, on the average, the same for each" ([30, p. 321]). Then:

$$(q_1 - k_1 U_1)\tau = (q_2 - k_2 U_2)\tau \Rightarrow U = \frac{q_2 - q_1}{k_2 - k_1} = \frac{\Delta q}{\Delta k} \tag{2.4.29}$$

The number of vehicles between the two observers remains the same. A point on the road between the passages of the two observers, will be passed by $q\tau$ vehicles. τ is fixed from the beginning, and it implies, as the authors state: "the flow q remains unchanged along the path of observers traveling with the speed" ([30, p. 321]) $U = \Delta q / \Delta k$.

LIGHTHILL and WHITHAM offer a literature review of the conjecture of "the flow q as a function of the concentration k" ([30, p. 321]). Most studies reported investigated flow-concentration relationships for either low or high values of concentration. The authors are among the first to assume, along with GREENSHIELDS in the 1930s (but perhaps more explicitly than him), to propose that "the information obtained from [low and high concentrations] should be combined into a single curve" ([30, p. 322]), but that the curve itself would summarize the section of road: "[flow against concentration] sums up all the properties of a stretch of road which are relevant to its ability to handle the flow of congested traffic" ([30, p. 322]), flow and concentration thus being "the two fundamental quantities" ([30, p. 322]).

This way, LIGHTHILL and WHITHAM define the general shape of the $q - k$ curve, the jam concentration and the capacity in a way that most models still use today. This can be summarized in three points, two limit conditions and the existence of a maximum between the two extremes:

- "as the concentration k tends to zero, the flow q must also become zero" ([30, p. 322]).
- "in the limiting case of high concentration $k = k_j$ (j for jam), the vehicles traveling in a given direction are packed tight on the part of the road where they are permitted to be; the flow q is then again zero" ([30, p. 322]).
- by application of the Rolle's theorem, "for some value of the concentration [k_m] between these two extremes, the flow q must have a maximum q_m which may be called the capacity of the road" ([30, p. 322]). In other words, this is the mathematical definition of the "critical point" of the *Highway Capacity Manual.*

As the authors state, k_m and q_m can be determined by observing a stationary wave $c = 0$. It then allows them to be more specific on defining a "crowded road" ([30, p. 324]): "a road is crowded if any increase in concentration will lead to a reduction in [space] mean speed" ([30, p. 324]). The model proposed by LIGHTHILL and WHITHAM is therefore "applicable only to long, 'crowded' roads".

2.4.3 "Discussion of traffic stream measurements and definitions"

EDIE is known in the traffic engineering world for his contributions in the 1950s and 1960s. His first major work, "Traffic delays at toll booths," was published in 1954. He was an engineer at the Port of New York Authority, the authority in charge of the bridges and tunnels, among other things, in the New York City area. EDIE's work aimed at finding an optimal way of staffing the toll booths, in balance between the cost of personnel and the delays suffered by the traffic passing through. His approach based on the "tools of probability theory" ([53, p. 107]) allowed to reach "savings in toll collection expenses and better service", whereas previously "experience and a rule-of-thumb work standard" ([53, p. 107]) were used to staff the toll booths, but "had

Variable	Short roadway dx–long time T	Short time dt–long roadway X
Flow q	$q = \frac{n}{T} = \frac{n}{\sum_i h_i} = \frac{1}{\overline{h}}$	$q = u \cdot k = \frac{\frac{\sum_i \mathrm{d}x_i}{X}}{\mathrm{d}t} = \frac{\sum_i u_i}{X} = \frac{\sum_i u_i}{\sum_i s_i} = \frac{\overline{u}}{\overline{s}}$
Concentration k	$k = \frac{\frac{\sum_i \mathrm{d}t_i}{T}}{\mathrm{d}x} = \frac{\sum_i \frac{1}{u_i}}{T} = \frac{\sum_i \frac{1}{u_i}}{\sum_i h_i}$	$k = \frac{n}{X} = \frac{n}{\sum_i s_i} = \frac{1}{\overline{s}}$
Speed u	$u = \frac{q}{k} = \frac{n\mathrm{d}x}{\sum_i \mathrm{d}t_i} = \frac{n}{\sum_i \frac{1}{u_i}}$	$u = \frac{\sum_i \mathrm{d}x_i}{n\mathrm{d}t} = \frac{\sum_i u_i}{n}$

Table 2.1 – Definitions of flow q, concentration k and space-mean speed u in both the "short roadway–long time" and "short time–long roadway" cases. Reproduced from [48, p. 141].

not been related to service" ([53, p. 107]). In other words, the tolls staffing policy did not always provide minimum delays to traffic.

A decade later, in 1963, Edie, in "Discussion of traffic stream measurements and definitions," generalizes the traffic variables independently of the means of observing it.

The fundamental idea behind his development is to describe the traffic stream continuum by its underlying vehicular trajectories: "each vehicle trajectory [is considered] through a given area of space and time to be a vector (x_i, t_i) where x_i is the distance traveled and t_i is the time taken by the ith vehicle" ([48, p. 139]).

The traffic stream is described by its flow, its concentration and its speed, and their variation in space and time. As Edie states, the definitions, already formalized by Wardrop and Lighthill and Whitham are "operational, i.e., associated with how the measurements are made" ([48, p. 140]).

Edie recalls the definitions of Lighthill and Whitham, at a given point x, and of Wardrop, which included the speed taken over two successive instantaneous aerial photographs of the same road section. These definitions, originally expressed by differentials dx and dt, analytically translating the small space or time increments considered, can also be expressed as functions of s_i (spacing) and h_i (headway) of each of the i vehicles.

For the sake of clarity, table 2.1 reproduces the definitions given by Edie in his paper [48, p. 141].

After some thoughts about the combination of either short roadway observations for different times, or short time observations for different road sections, Edie proposes so-called "Revised definitions" ([48, p. 143]).

The new set of definitions of flow q, concentration k, and speed u, is "independent of methods of measurement", and valid for any space-time domain. A *space-time domain* is "any enclosed portion of a space-time plane".

A designates the area of the space-time domain.

The flow q of a traffic stream is "the aggregate distance traveled by all vehicles passing through a space-time domain divided by the area of the domain" ([48, p. 144]):

$$q = \frac{\sum_i x_i}{A} = \frac{\text{aggregate distance traveled}}{\text{area of } A} \tag{2.4.30}$$

The concentration k of a traffic stream is "the aggregate time spent by all vehicles in passing through a space-time domain divided by the area of the domain" ([48, p. 144]):

$$k = \frac{\sum_i t_i}{A} = \frac{\text{aggregate time spent}}{\text{area of } A} \tag{2.4.31}$$

The speed u of a traffic stream "in a given space-time domain is the aggregate distance traveled divided by the aggregate time spent by all vehicles traversing it" ([48, p. 144]).

$$u = \frac{\sum_i x_i}{\sum_i t_i} = \frac{\text{aggregate distance traveled}}{\text{aggregate time spent}} \tag{2.4.32}$$

This work is fundamental, especially today as means of observations both vary through time and space. The definitions he provided appear to be very stable, as they are used even very recently [54].

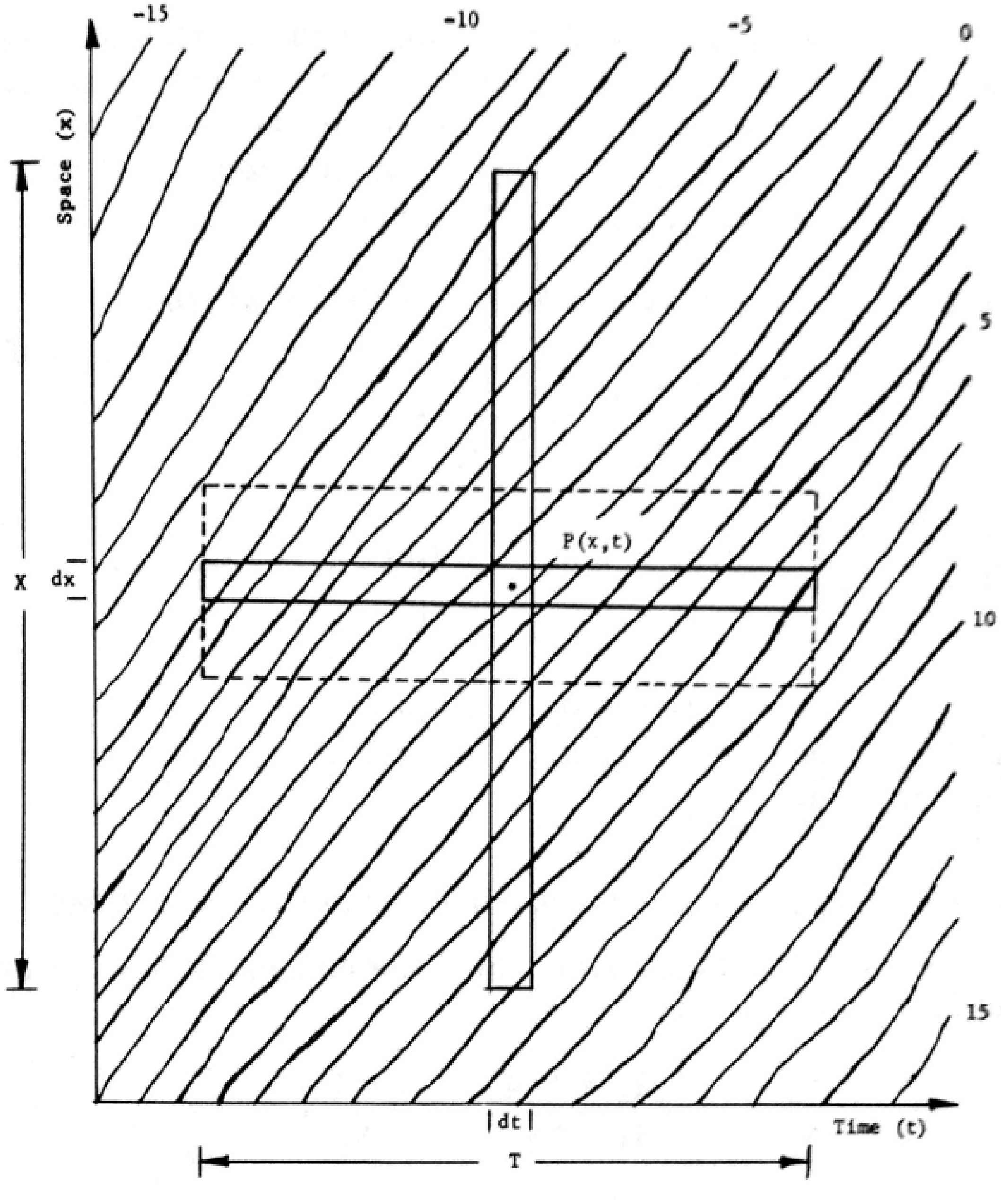

Figure 2.4 – EDIE, 1963, fig.1 p.141. Measurements of a traffic stream at point (x, t) by two methods.

2.4.4 *Mathematical Theories of Traffic Flow*

The final milestone of the 1930s-1960s era of traffic variable definition, probably is HAIGHT's *Mathematical Theories of Traffic Flow* [49]. Like his predecessors', his motivations are worth noting: traffic engineering, more particularly traffic flow, is for him part of "the scientific study of congestion" ([49, p. v]), since "as a source of congestion, the motor vehicle occupies a unique position" ([49, p. v]). He aimed at exposing the existing "considerable literature in traffic flow theory", while "not trying to 'solve the traffic problem'". The purpose of the "mathematical theories [is to] define, characterize, and describe one specific phenomenon: vehicular traffic" ([49, p. vi]). Traffic flow theory is still seen as "immature" ([49, p. vi]), and "there is no general agreement on notation or terminology, most of which has been inherited from the traffic engineer" ([49, p. vi]). It must be nonetheless stated that fundamental traffic variables, as seen through these pages, had at last precise definitions. He even added that "there is very little agreement on methodology, or on which quantities are significant, or on how these quantities should be measured". HAIGHT's statement might be a little bit overblown: flow, concentration, speed nonetheless were matters of importance both for the engineers and the modelers, as successively shown by the works of GREENSHIELDS, WARDROP, LIGHTHILL and WHITHAM, and EDIE. These authors had already provided some converging definitions for the fundamental variables of traffic taken as a stream. HAIGHT aimed at anchoring traffic flow theory onto the field of applied mathematics: "the first attempt to justify the theory as a sensible part of applied mathematics" ([49, p. vii]).

After developments on general statistics and theories of queues, HAIGHT gives the "Fundamental Characteristics of Road Traffic" ([49, pp. 67–95]). The two aspects of studying traffic, empirical and theoretical, are well illustrated by the "time-space dichotomy" ([49, p. 69]), i.e. the distributions in time and space of cars are not identical. HAIGHT clearly identified the difficulties of empirical measurements: "relationships between cars in space and cars in time have a particularly important role to play in empirical studies, for the time measurements are characteristically easy for the traffic engineer to perform, whereas space measurements require, at present, extremely accurate and far reaching aerial photography".

In this context, HAIGHT was among the earliest calling the flow-concentration diagram the "Fundamental Diagram of Road Traffic" ([49, p. 72]), and derives it both for the two types of traffic models, car following and fluid flow models. With this name, the flow-concentration relationship was clearly identified as the cornerstone of traffic theory.

Traffic flow variables are: flow, concentration, speed. These are brought up as the analogy between traffic flow and the fluid theory, already felt in the 1930s, is formalized. The definition of the variables remains closely associated to how they are measured, schematically either from a spot on the road (Eulerian observer) or by a moving observer (Lagrangian observer).

They are defined over a rather imprecise scale by WARDROP, and then by LIGHTHILL and WHITHAM: EDIE proposed a generalization of the definitions over a random space-time area, which somehow solved the problem at least analytically. Nonetheless, the minimum time duration of spot observations remains a question.

The average issue (either space or time) is closely linked to method of data collection (spot observation or from the air), as identified by the authors. Time-mean speed is the easiest to collect at a point on the road, whereas the meaningful speed for drivers is the space-mean speed, which is the reciprocal of journey time.

The relationship between flow, concentration and speed becomes known as the fundamental diagram, and is meant to summarize the resulting interaction between demand (drivers) and the supply (infrastructure), which is traffic.

2.5 Traffic indicators for network assessment

Traffic indicators are companions to traffic data. Most traffic data is the result of punctual measurements, originally traffic counts, then followed by traffic spot-speeds, etc., needed to be summarized into global figures that could help the decision-making process. The rising number of punctual measurements stressed the need for over-all, summarizing figures that could offer a common-basis of comparison as well as a fairly straightforward understanding by individuals not necessarily familiar with all the subtleties of the traffic engineering field.

Among the variety of traffic indicators produced, vehicle miles traveled and travel-time (and associated speed, which is the space-mean speed) stand out as they turned out to be, since the 1910s-1920s, two key variables used in traffic-related decision-making.

This section, which presents these two indicators, also presents some of the encountered operational issues in measuring them with mostly ground-based techniques.

2.5.1 Vehicle miles traveled, vehicle kilometers traveled

One of the earliest road traffic indicators, empirically linked to traffic counts, is the *vehicle miles traveled indicator* (VMT, when used with the imperial system) or *vehicle kilometers traveled indicator* (VKT, when used with the metric system). In the United States, the Federal government has been elaborating this indicator since at least 1936, and it was included in the Federal *Highway Statistics* series, which started to be systematically published on a yearly basis in 1945 [56].

VKT is the sum of the distances traveled individually by each motor vehicle over a given network and a given period of time. Much like traffic counts, this figure has been primarily used for highway maintenance and planning, and in close relation with traffic safety. The 1973 oil crisis led to increased concerns for fuel consumption, and the energy aspect added up to the motivations behind the VKT [57]. In 1979, Rudman [57] mentions three ways used of estimating VMT in the United States (each State having the freedom to whatever method it found suitable to compute its State VMT, then aggregated at Federal level by the FHWA):

the traffic-count procedures, which "assumes that the vehicle kilometers traveled [...] can be estimated by counting the traffic on representative sections of roadway (links) [...]" ([57, p. 20]), a link being "a section of roadway that has homogeneous traffic volume" ([57, p. 21]).

the fuel-consumption method, which "assumes that vehicle kilometers traveled [...] is a function of the fuel-consumption rate and the number of liters of motor fuel consumed by vehicles in one year" ([57, p. 22]).

the Nationwide Personal Transportation Survey, a "cross-section study of 6000 households in 1969-1970" ([57, p. 25]), which examines "variables that were relevant to aggregate vehicle kilometers traveled considerations includ[ing] the number of automobiles per household, origin and destination of trip, urban versus rural travel, discretionary versus necessary travel, age of automobile, income and vehicle kilometers traveled correlations, and annual kilometers of automobile travel" ([57, p. 25]).

All of these methods provide estimates, as the exhaustive measurement of it is out-of-reach with standard ground-based techniques.

The American motivations and methods can be extended to Europe, and cities like Paris used daily VKT to quantify the traffic trend on their networks [58, p. 17].

2.5.2 Travel-times and Speeds

As seen before, a journey can either be considered through its average speed (the space-mean speed) or its travel-time. Spot speed has been given much consideration since the beginnings of traffic engineering. The reason behind this is mainly technical: it only required one or two observers, and automatic detectors (like dual loops) made the task even easier. A good deal of the traffic theory was then to transform this spot-measurement into the relevant spatial quantities.

Nonetheless, travel-time remains the most straightforward quantity, and has been investigated early in the traffic engineering literature, although the complexity of the task made its collection tedious and expensive.

Moreover, it took until WARDROP's paper in 1952 to have a proper definition of speed, both for spot-speed interpretation, and journey-speed interpretation. The latter was called "over-all speed".

The basic method to estimate travel-time is similar to the estimation of VKT from traffic counts. The route considered is divided into segments, each associated with a spot-speed station, each carefully selected with rule-of-thumb methods guaranteeing they were not "specific" but "meaningful". For each segment, the travel-time is its length divided by its measured spot-speed. The route travel-time then is the sum of the section's travel-time.

Another, rougher method, was to average all spot-speeds (arithmetic average) and then divide the route's length by the resulting speed.

Travel-time measurements represented a significant break in the way traffic was measured. Spot-measures, counts, then complemented by speeds, allowed collection of information on nearly-all vehicles passing by. Extensive travel-time measurements required to sample not only the observation periods, as for the counts, like with MCCLINTOCK's 1935 short count traffic surveys, but also sample which vehicles would be tracked by observers.

In the 1930s, travel-time measurement campaigns began to rely on two different techniques.

The first method is based on fixed points of observation, and uses vehicle re-identification. Take a route from A to B, and place observers at the route's entrance in A and route's exit in B. The observers record vehicles' plates for a given period of time. Various recording mechanisms allow a more or less approximate timestamping of the vehicles' passage: reporting pools of plates per intervals of a few seconds length, magnetic tape recorder, etc. This method was challenged in the early days, as reported by ROWLAND BIBBINS in 1935 [31].

The second method involves having a sample vehicle fleet traveling with the traffic. The vehicles are often fitted with dedicated apparatus recording their speed, the distance traveled, the time spent, etc. The method is referred to as "floating car" or "car floating with the traffic" apparently since its inception. Vehicles equipped with recording devices are mentioned in the 1920s [59]. The traffic engineering manuals reported the various philosophies of floating car techniques, called "Speed and delay studies".

In the late 1940s, the Highway Research Board launched a research program on "Operating Speeds in Urban Areas", in line with 1920s and 1930s studies. The purpose was "the development of a sampling technique whereby the speed of traffic on urban facilities can be measured on an annual basis with a reasonable degree of accuracy" ([60, p. 311]). In a series of two papers, BERRY and GREEN[7] reported "Techniques for measuring over-all speeds in urban areas" [60] and an evaluation of them [61], in order to "investigate the accuracy of test-car methods of measuring vehicular travel times on major streets controlled by traffic signals" ([60, p. 311]). Such test-car

[7] BERRY would later become chairman of the Highway Research Board, and overlook the 1965 edition of the *Highway Capacity Manual 1965* [43].

campaigns serve three purposes, according to Berry and Green:

- "a measure of congestion" ([60, p. 311]);
- "a means of identifying the causes and amounts of delays" ([60, p. 311]);
- "an aid in computing savings in travel time" ([60, p. 311]), which "may be in reference to completed or proposed improvements" on the road.

The first paper tested three already known methods of test-run techniques. The methods differed in the behavior of the test vehicle's driver. He either: 1. drives "at a speed which, in his opinion, is representative of the speed of all traffic at the time" ([60, p. 312]); 2. "maintain[s] a maximum speed consistent with safety and existing traffic regulations" ([60, p. 312]); 3. "maintains a place in the traffic stream, but to gage his speed by that of slower vehicles" ([60, p. 312]).

The reference travel-time was established through license plates recording at the two ends of the measured section.

The authors' work present not only average travel-times, but travel-times distributions and associated statistical indicators of dispersion (standard-deviation, interquartile range) yielded by the license check travel times. Besides the variations induced by the various methods, the authors made two key observations:

preeminence of signal timing on one of the routes, "vehicles travel[ed] at a fairly uniform speed, as shown by the high peak on the curve, as a result of the signal timing" ([60, p. 315]). This demonstrated that "signal timing [has] more influence on speed than differences in techniques of driving" ([60, p. 315]), i.e. signal timing is a key factor in how travel-times are distributed on a signalized arterial. The effect of signals could also be felt when considering the evolution of average travel-times through the day: "it may be noted that, in general, travel times decreased after the signal timing was changed [...], whereas traffic volume continued to increase" ([60, pp. 315–316]).

intersections delay "delays encountered at some [...] intersections" ([60, p. 315]) caused travel times to vary "considerably" ([60, p. 315]).

They concluded that "travel-time variation is much smaller for traffic below the capacity of the intersections" ([60, p. 318]), whereas it "varies greatly as the traffic volume on signalized streets reaches and exceeds the capacity of the intersections" ([60, p. 318]). Variability meant that "more test runs usually are needed during peak hours than at other times" ([60, p. 318]).

In all, the license check method was seen as "an accurate method of determining [the distribution of] travel times for all vehicles traversing the entire length of a test section" ([60, p. 317]), but remained nonetheless "expensive" ([60, p. 317]) in terms of manpower both to obtain and analyze the data. Hence the test-car method was brought forward for it required less manpower, and a few runs yielded a good estimate of the average journey speed of traffic if traffic conditions remain stable. The issue raised then was how "the standard 'floating car' technique" ([60, p. 318]), which involves, during the drive, passing as much vehicles as getting passed, would compare to "the 'average' test-run method" ([60, p. 318]).

Berry carried out the comparison between the floating car and average techniques a few years later [61], with license check still acting as reference. The mean travel-times yielded by both methods was compared with the distribution of license checks travel-times. The experiment showed that "floating test cars produce results that are less reliable than the results obtained with the same number of runs of average cars" ([61, p. 439]). The reliability was measured by the distribution dispersion, which appeared to be more compact for average runs than floating car runs. In a general sense, the authors assumed that "test-car runs produce more compact distributions than license-check distributions, since test-car drivers are consciously trying to approximate the predominating speed of traffic" ([61, pp. 434–435]). Although very sensitive to the selected drivers behaviors, the solution such appeared cheaper than floating car runs which in the end should converge toward the general travel-time distribution, as approximated by the license-checks, but would require more runs. Again, the fear of variability and search for a "compact" distribution, so that central tendancy indicators such as the mean or the median would mean something, overweighted the physical aspect of travel-times: the importance of their variation, and the quantification of that variation, is as much an indicator of performance as the central tendency.

Starting in the early 1960s, in the United States, the development of electronic tolling devices allowed the widespread collection of travel times. Each vehicle was identified at each toll plaza it crossed by its payment beacon or its license plate [62].

The operational needs calling for global indicators, such as vehicle kilometers traveled and travel-times, were already identified in the early days.

A compromise with the available technology had to be found.

This is true for vehicle kilometers traveled estimates. It relies on traffic counts, which are "easier" to collect than any other traffic data. It also depends on the average length of trips, which is much harder to catch.

Travel-time is a step further in complexity: various and more or less complex sampling method were set up, but that would only give partial results at great cost. Studies of travel-time however raised remarks on their distributions that are still valid today. Moreover, much more importance was given to central tendency indicators, and methods sought to reduce the spread of the distributions, overlooking the physical meaning of dispersion.

2.6 Traffic data in Paris: from manual counts to centralized collection

This section presents the technical aspect of the traffic data collection in Paris, from its inception in the early XXth century, to the centralized traffic management scheme of the late 1970s. This evolution will be related to what was stated in the previous sections on the traffic theory and the research on traffic variables.

We show that two aspects of traffic have been considered: the earliest is the volume, and traffic counts have played a key role from the beginning. It was, a few decades later, followed by time, with estimates of speed and travel-times. At last, the centralization of traffic lights coordination lead to the creation of an automated traffic data collection system that could serve the political agenda.

2.6.1 Traffic counts

In France, carriage inventories were made mandatory for military purposes. A law of 1877[8] obliged municipalities to draw such inventories every three years, to allow requisitions if need be.

The City of Paris started, in 1880, the annual edition of a statistical directory for its territory, the "Annuaire statistique de la ville de Paris." "Traffic", which included both private-owned carriages and public transport, had a dedicated chapter. The next year, in the 1881 edition, along with the carriage and animals inventory, the City reported the results of several hundred 24-hour traffic count surveys it carried out in 1881-1882 [64, pp. 506–525]. These counts included,

[8]The Loi du 3 juillet 1877 relative aux réquisitions militaires (titre VIII)

for each location, the type of pavement, the road width, the number of carriages and of collars counted on average per 24-hour periods.

The next traffic counts reported in the directory series were made almost thirty years later, in the 1907 edition, with the counts made in 1908 [65, p. 379][9]. For the first time, automobiles and buses appear, along with previously reported horse-drawn carriages. The counts are reported for four locations in central Paris, and were made from 13:00 to 19:00. Horse-drawn carriages figures of 1881 are also inserted to allow comparisons.

The need for traffic data in Paris increased in the 1900s, with people like HÉNARD, a French architect and urban planner, who highlighted the key role traffic, and more specifically the car, was to play in the future. Therefore, such planning required a proper quantification of traffic [66, p. 78]. Traffic counts campaigns would then be carried out on a regular basis, and some of their results published in the yearly editions of the "Annuaire statistique de la ville de Paris."

Between Paris and its suburbs, the first "reliable" traffic counts were carried out at Paris gates in the mid-1930s, although no contextual information is given [66, p. 90]. As FLONNEAU reports, private cars were still mostly driven during the good season, and so the volumes recorded at that time, without any complementary information, are hardly useful.

After the Second World War, like in many other Western cities, motor traffic dramatically increased in Paris. The public authorities held a growing concerns on the rise in automobile demand, and various projects began to emerge. The Préfecture published successive reports on road traffic in Paris, in 1951, 1953, 1961, 1974, and 1975 [66, p. 154]. Behind the scenes, there was the need for traffic data to fuel these various studies, and the major infrastructure projects that came along them:

- first of all, the Boulevard Périphérique, Paris ringway, which opened in stages between 1960 and 1973;
- second, a master plan calling for expressways in inner Paris, supplemented by local grade-separations and the creation of parking lots.

The political context of the 1950s-1970s era is drawn in detail by FLONNEAU [66].

By the late 1960s, as the ringway was almost complete, along with major radial motorways, traffic volumes in Paris kept increasing. In 1968, TESSIER, an engineer, carried out a thorough study using a totally new methodology, based on computer simulation, anticipating, following five scenarios, the traffic conditions in central Paris once the expressway plans would be completed [67].

Growing social concerns, along with the 1973-1974 oil and ensuing financial crisis, brought the major infrastructure schemes to a halt. Moreover, most critical urban junctions had already been grade-separated.

In the aftermath of the cancellations, the Préfecture issued two key reports on traffic in Paris: an analysis report, *Analyse de la circulation à Paris*, in 1973 [68], and a white paper, *Le Livre Blanc de la circulation*, in 1975 [58]. The report was to answer the anticipated "unacceptable scenario" ([58, p. 37]) of a 17 % increase of daily journeys to or from Paris, with a modal share of the car that would increase from 37 % to 54 % of these journeys.

In this context, among other measures, the Paris Administration initiated the work on a comprehensive demand management system for the city, which would replace preexisting equipments[10]. The question was now more to manage the network, rather than expanding it. The white paper even mentioned the criticality of insufficient funding for the traffic signals since the

[9] Each volume of the "Annuaire" was published the year that followed its number, hence it could include data collected during its publication year.

[10] Local traffic lights coordination had already been implemented in some sectors, starting in 1948. Successive schemes over small areas of the city were then carried out throughout the 1950s and 1960s.

1960s: “Regarding traffic management, Paris, for long ahead of everyone, was now falling behind” ([58, p. 36]) other cities.

These studies, like past road authorities reports, relied on traffic data. The 1973 report views traffic conditions in terms of volume, speeds, accidents and parking issues. Traffic counts relied both on automatic fixed or mobile sensors, and on manual counts. The first automatic fixed sensors installed in Paris were pressure-sensitive treadles, likely of American technology, in the late 1940s and 1950s. Most modern automatic traffic sensors were conceived in the late 1920s, early 1930s by the Yale University, the prototype of pressure-sensitive detector having been experimented in New Haven in 1928 [2, p. 75][11]. The first traffic-actuated signals with this pressure technology were then implemented, and quickly spread across the country during the 1930s, despite the Great Depression [2, pp. 76–77]. Montreal had a pressure-sensors based system managing 50 junctions within its Central Business District in 1933, which was the first reported system at this scale [2, p. 135]. The treadles also allowed to collect spot speed [2, p. 139]. During the 1930s, other detectors also appeared, like the modern-day traffic loop: “In addition to the sonic and pressure-sensitive devices, manufacturers introduced various types, including those using sonar, radar, infra red, photo-electric cell and magnetic detectors, and those actuated by a change of inductance of an electric circuit during passage of a vehicle” ([2, p. 135]). After the war, with the computer breakthrough, the reportedly first extensive traffic lights computer-supervised system, at least in the United States, went live in Denver in 1952. It controlled 120 intersections and relied on one computer and six pressure-sensitive detectors [2, p. 141]. Ten years later, in 1963, the Toronto system, took a further step: “through leased telephone lines, the large computer was connected with the signals ; and, to provide the computer with actual traffic flow data, a large number of vehicle detectors were installed” ([2, p. 143]).

In Paris, as reported in the 1973 analysis report [68], traffic count surveys were carried out at the network’s scale in 1953, 1963 (only the Southern segment of the ringway was opened), 1969 (the Right bank West to East cross-town expressway was opened, and only the Western segment of the ringway, due to open 1973, was missing), 1970. The report mentions eight fixed traffic stations, and about 14 inductive loops detectors on the opened South, East and North sections of the ringway.

Traffic statistics went a step further in the late 1970s, following both the white paper of 1975, and State-levels instructions given in 1975 on road traffic surveys.

The completed ringway, with its motorway-like characteristics, became a specific road within Paris road network. It then had a dedicated department of the Direction de la Voirie, followed dedicated regulations inherited from the State motorway administration. A dedicated management and data collection system was set up, relying on traffic loops detectors.

Meanwhile, a comprehensive traffic plan was setup in 1976 for the inner Paris network, defining a main arterial network (“réseau principal de voirie”).

On January 1st, 1978, in the line of the traffic plan, a traffic survey plan covering the City of Paris was set up [69, 70]. The survey covered the main arterial network defined in 1976, complemented by some other corridors used by bus routes. It defined both the data collection equipments and the statistics to be carried out.

The survey network is divided into sections, each being defined as not have a flow variation over 20 % between its entrance and exit. Each section bears an either temporary or permanent traffic station, positioned in order to be “representative of the average flow of the section” ([69,

[11] At the same time, in 1928, another experiment was installed, involving a traffic-actuated device which was sound-responsive, and required the driver to honk is horn to trigger the signal: the so-called Adler device, from his inventor Charles Adler Jr., who worked on railway signals [2, p. 73].

p. I2]). Permanent traffic count stations were installed at the most representative locations of the network, and at regular intervals on the ringway. Sections not equipped with permanent stations, but temporary ones, were counted by mobile devices, with a frequency that varied depending on its traffic levels (one month every two month, two weeks every four years, or on demand for more local streets). In 1979, most stations relied on pressure-type technology, but there were already a few electromagnetic detectors for the inner Paris network, and all expressways and the ringway were equipped with electromagnetic detectors. In total, in 1979, there were 145 counters used for fixed or mobile sites [69, pp. II1–II2]. A computer system was designed to aggregate the data (different formats were produced, depending on the detectors' models) and compute the statistics.

Among the statistics, two key figures were computed and published: the average daily traffic (the 24-hour flows averaged through the year), and the associated VKT.

The first synthetic report on the traffic count survey method was published in late 1983, and covered the 1978-1981 period. Traffic volumes could even be compared with yearly figures from 1967 onwards: the report mentions these five fixed traffic stations installed in 1967 on major arterials, the same year the Right Bank expressway was inaugurated.

The centralized traffic management system would dramatically change the scale of traffic measurements. Following the 1973-1975 studies, in 1976, the Roads authorities published a preliminary report for a centralized traffic management system in Paris, *Rapport préliminaire sur la régulation du trafic à Paris* [3]. Along with the traffic plan, it would become the second pillar of surface transport management in the City. The project was voted by the Conseil de Paris (city's parliament) during its June 23, 1977 session. A note on the traffic management system [71], in 1982, was a progress report on the project. The system was an answer to "the rigidity of current[12] practices [that had] led to a poor efficiency of the network" ([71, p. 1]), and was aimed at:

- "lowering travel-times" ([71, p. 1]);
- "improving the surface public transport network performances" ([71, p. 1]), which at the time consisted solely of buses, some line sections running on dedicated lanes;
- "easing the movement of emergency vehicles" ([71, p. 1]);
- "improving ground assets availability" ([71, p. 1]) thanks to "the centralization of the alarms raised by faulty equipments" ([71, p. 1]);

The system also allowed to renew obsolete material and improve junctions' safety.

The first phase of funding included a temporary traffic management center (the final facility, still in use today, was only completed in the late 1980s) and included traffic monitoring equipments (synoptic, consoles, etc.), two computers (one for real-time operation and one backup), the connection of 43 junctions in central Paris. This first phase was completed in May 1981. The second and third phases extended the junctions coverage by respectively 16 and 47 junctions, and were completed by late 1982. New junctions were then gradually wired throughout the 1980s. The system became known as SURF, acronym standing for Système Urbain de Régulation des Feux, Urban system for signals management.

The system management algorithm relied on ground measures carried out by fixed sensors. The technology used was the electro-magnetic inductive loops, instead of the former pressure-type detectors. The loops allowed occupancy and flow measures at key locations, feeding the algorithms. Nonetheless, the engineers involved behind the project had the insight to install more sensors than required for signals actuation:

[12] i.e., before the traffic management system.

- additional occupancy measures, even at locations not in use for algorithms, in order to retrieve the traffic state for all the managed arterials;
- additional flow measures, for statistical purposes, in line with the traffic count survey plan.

In order for the traffic operators, in the control room, to have a global view of the system in real-time and in a glimpse, the managed network had to be modeled. Formerly, this did not happen until the early 1990s system upgrades: before, traffic states were simply represented by a colored light embedded in the map panel of the control room. A simplified, although overall geographically accurate, model of the road network was designed. The road network was represented by an oriented graph, each link representing an oriented one-way road section. This means that a two-way road from A to B would be represented by two parallel links, one from A to B, and one from B to A. The traffic sensors were then associated with the links: the additional traffic sensors, though not used by the signals actuation algorithms, would display information on the traffic state to the control room. The main assumption behind this, like the one made since the inception of traffic spot observations, is that the spot measurement on the length $\mathrm{d}x$ made by the loops during a time $\mathrm{d}t$ would be relevant for a specific section Δx, with $\Delta x \gg \mathrm{d}x$. Therefore, the definition of sections took into account the network topology (no signalized junction in the middle of a link), and the position of each sensor was often carefully studied. A practical case was that occupancy should be measured away enough from the next downstream traffic light stop line, so that in free-flowing conditions, no car waiting at the downstream red would be stopped over the sensor, which would then report inaccurate traffic states. In other words, some rule-of-thumb of typical queue length in free-flowing conditions was drawn, probably in a way based[13] on the Poisson approximation of traffic and Little's law, that yields the average length of the queue.

Throughout Paris, the traffic sensors followed the same technical specifications. They were all inductive loops embedded within the roadbed. The electrical signal from the loops is processed by the associated detector, which then sends signal to the junction's controller that itself transmits the data to the central computer.

Two types of data are available: occupancy and flow, polled every 5 s between the controller and the central computer, which itself aggregates them into 3 min intervals. The 3 min data is then used as an input to algorithms and stored into the database.

Occupancy is systematically measured on all sites, as it is the main input to SURF algorithms.

As there are generally no lane markings on Paris streets, traffic count sites are designed according to theoretical 2.70 meter-wide lanes. The general rule is to implement a row $2n - 1$ loops on a section with n such lanes, perpendicularly to the traffic direction. Each loop is a one by one meter square. A truth table interprets the loops signal variations as to eliminate double counts when a single car passes over several loops.

Junctions were gradually wired with the system until the 2000s. The traffic management center itself was moved into its final facility, still in use today, in the early 1990s. It then became known as the Poste Central d'Exploitation Lutèce, or PCE Lutèce.

2.6.2 Centralized traffic data collection to quantify the traffic state: from assessing the system performance to measure the decrease of traffic demand

The first assessments of the "efficiency" ([72, p. 30]), also called "performance" ([73]), of the SURF system were carried out on the monitored network in 1983-1984. Their results were

[13] Despite his intensive archive digging, the author could not find any trace of it.

published in a series of reports in 1983-1984, among which the 1984 *Régulation centralisée du trafic (premiers résultats)* [73]. Note the close relationship between the system, the road network, and the traffic traveling on it: infrastructure (the road and its assets) and the service provided (traffic conditions) were now deeply linked through the SURF system. Speaking of network performance or system performance would therefore mean the same thing in the technical reports. To keep track of this strong relationship, this will therefore be designated as the SURF system performance. Despite a centralized occupancy and flow data collection and recording, these variables, "with the knowledge [of the time], did not allow to precisely measure the network's performances" ([73]). Two means were therefore employed for the assessment studies.

The first method, the quickest to be analyzed and yield results, relied on dedicated test cars running according to the floating car technique, and fitted with magnetic tape recorders. They were sent into traffic on nine routes. For each route, test runs were made before and after its junctions were connected to the central system. The performance was assessed by three parameters: trip time, trip regularity, and stop time. Each of these were recorded per vehicle and per run, i.e. microscopic variables. Distributions of these variables were then analyzed.

The second method involved aerial photography [74]. The engineer Robin-Prévallée carried out the study, published in early 1986. Extensive aerial surveys had been carried out throughout the 1970s over some of Paris region départements: Val-de-Marne in 1972, Seine-Saint-Denis in 1973, Hauts-de-Seine in 1975, Essonne in 1976, the City of Paris proper in 1970 and 1977. The purpose of these surveys were to get the average traffic situation at the scale of networks, which required several surveys at different time of day and of the year. This turned out to be very costly in terms of manpower and equipments, and the aerial survey programs, which were originally meant to become periodical, ended up being axed. Nonetheless, in the early 1980s, the inception of the SURF system for central Paris raised the interest for a new punctual survey limited to central Paris. Two surveys were carried out before (June 1982) and after (June 1983) the first phase of the system was turned on. The assessment parameters were this time not microscopic as with the test runs, but macroscopic, i.e. directly related to the traffic stream: the concentration and the average speed. The "concentration" is the number of vehicles within the zone of survey. The "average speed" is the arithmetic average of the speeds of vehicles within the zone of survey. The speed of a vehicle is computed from the distance it travels between two overlapping successive pictures, like in 1929 during Johnson's campaign. In the 1982-1983 Paris surveys, the two overlapping pictures were taken in a 10 s intervals, and the vehicular speed derived was considered to be the instantaneous speed. The plot of speed against concentration for a zone, called by Robin-Prévallée the "characteristic diagram" ([74, p. 13]), also called the "performance diagram" ([74, p. 13]), was used to assess the SURF system. Such plots later became known as Macroscopic Fundamental Diagrams in the literature.

These two surveys and their methodologies and results, were used at a broader scale by the Groupe de travail de la régulation en Ile-de-France, the Working group on traffic management in Ile-de-France. In a report [75] published just a few month after Robin-Prévallée's report on Paris aerial surveys, the Working group synthesized the issues and methods available to compute traffic indicators to assess traffic management systems efficiency. The purpose of such network-wide indicators is clearly stated: "Has the management system fulfilled the goal it was designed for? How is the level of service it provides evolving?" ([75, p. 7]).

Test-cars and aerial surveys operations turn out to be very demanding, both financially and for post-processing workforce. This triggered intensive cooperation between the State Research Institutes[14] and the City of Paris Direction de la Voirie to use the existing SURF sensor in-

[14]INRETS, Institut national de recherche sur les transports et leur sécurité, National research institute on

frastructure (occupancy and flow measures) to elaborate automatic indicators measuring the "improvement of the quality of trips" ([72, p. 30]) through the "continuous monitoring of traffic" ([72, p. 34]). The SURF performance was that of the traffic on the network it manages, likewise the network performance was that of the traffic. In terms of traffic data, this meant monitoring the volume and time spent on the network.

The term "corridor", or "SURF corridor", designates a directed route on the network. Onto the oriented graph modelling the road network, a corridor is a finite directed path: a finite set I of n oriented links. Each link $i \in I$ has length L_i and is associated with a flow sensor Q_i and an occupancy sensor O_i. As stated above, for a given corridor, i.e. set I of links, there are often fewer flow sensors than links: the same flow sensor can therefore be associated with several links, the same way that in traffic surveys, a count station would be considered relevant for a specific road length.

The "network" can then be seen as a finite partition of corridors, as for evident statistical purposes (not counting twice the same roads!), corridors do not overlap.

Volume and time spent are extensive quantities, and can therefore be summed with respect to time and space.

Time-wise, a volume is computed over a time interval "of moderate length τ [...] long-enough for many vehicles to pass" ([30, pp. 319–320]), as mentioned by Lighthill and Whitham. In the same spirit, both volume and time spent are defined over a time-frame τ, $\tau \gg \mathrm{d}t$, $\mathrm{d}t$ being the elementary time-scale measurement of the traffic sensors as transmitted to the central system (in Paris, every 5 s).

Space-wise, the indicators are therefore valid for a corridor as well as for a network.

The volume indicator is the VKT. The VKT_i on a link i is, for time-frame τ, its length L_i weighted by the flow $Q_i(\tau)$:

$$VKT_i = L_i \times Q_i \tag{2.6.1}$$

Therefore, the VKT for either a corridor or a network, and for a time-frame τ, is:

$$VKT = \sum_i VKT_i = \sum_i Q_i \cdot L_i \tag{2.6.2}$$

It relies on the assumption that the flow measured at one location remains constant over one or several links.

The VKT can also be normalized by dividing it by the set of links (corridor or network) total length $L = \sum_{i \in I} L_i$. It is then homogeneous to a flow, and can be regarded as a "virtual traffic count station" accounting for the entire set of links (corridor or network) for a time-frame τ:

$$VKT_{norm} = \frac{\sum_i Q_i \cdot L_i}{\sum_i L_i} \tag{2.6.3}$$

The time spent TS_i on a link i, during τ, is the average travel-time $\overline{t_i}$ weighted by the flow Q_i:

$$TS_i = \overline{t_i} \times Q_i \tag{2.6.4}$$

transport and its safety, which merged in 2011 with the LCPC, Laboratoire Central des Ponts et Chaussées, Central Laboratory of Ponts et Chaussées, creating a new State institute, IFSTTAR, Institut français des sciences et technologies des transports, de l'aménagement et des réseaux, French institute of sciences and technologies for transport, development and networks.

Therefore, the time spent TS, during τ, for either a corridor or a network is:

$$TS = \sum_i TS_i = \sum_i \overline{t_i} \cdot Q_i \tag{2.6.5}$$

The average travel time $\overline{t_i}(\tau)$ was estimated based on the flow and occupancy measures. The data collected during the test car runs in 1983 was used in the research study on the relationship between occupancy and travel-time. In 1985, ABOURS stated in the resulting research report based on the test runs data, *Estimation des temps de parcours sur axe urbain à partir de taux d'occupation* [76], that the relationship between occupancy and average travel-time on a corridor could be considered linear:

$$\overline{t_i}(\tau) = \alpha_i \cdot O_i(\tau) + \beta_i \tag{2.6.6}$$

The coefficients α_i and β_i are independent of the time-frame τ of observation, but are dependent on the link i. The 1986 report on traffic indicators [75] concluded on the first results of this study, and opened up on the perspectives offered by the methodology. At last, what was then perceived as a financially feasible and reliable way to assess traffic conditions in real-time over a road network could become available!

ROBIN-PRÉVALLÉE, in the line of his work on network-wide macroscopic variables, based on the aerial surveys of 1982-1983 and ABOURS's 1985 work, derived the final analytical expression of the network-wide indicator based on flow and occupancy measures.

In 1987, BONVALET and ROBIN-PRÉVALLÉE derived an analytical expression for α_i and β_i by assuming limit conditions at a macroscopic scale, and not on a per-vehicle basis as ABOURS:

- if $O_i \to 0$, then the travel time nears a constant value $t_{0,i}$ (free-flow situation), yielding

$$\beta_i = t_{0,i} \tag{2.6.7}$$

- if $O_i \to 1$, then $Q_i \to 0$ and the area can be considered as full. The total time spent on it per time unit is then $N_{max} \times O_i$. By definition of the total time spent per time unit, $Q_i \times t_i = N_{max} \times O_i$, yielding:

$$\alpha_i = \frac{N_{max}}{Q_i} - t_{0,i} \tag{2.6.8}$$

The average travel time $\overline{t_i}$ of link i for the time frame τ then becomes:

$$\overline{t_i} = t_{0,i} \times (1 - O_i) + \frac{N_{max} \times O_i}{Q_i} \tag{2.6.9}$$

The ratio of VKT to TS, homogeneous to a speed, became known in France as the "BRP speed" or "BRP indicator", from its authors, BONVALET and ROBIN-PRÉVALLÉE. The BRP speed, V_{BRP}, like its numerator and denominator, is defined over a set I of links i and a time frame τ, with flows $Q_{i\in I,\tau}$ and occupancies $O_{i\in I,\tau}$:

$$V_{BRP} = \frac{VKT}{TS} = \frac{\sum_i Q_i \cdot L_i}{\sum_i \overline{t_i} \cdot Q_i} \tag{2.6.10}$$

From this average speed V_{BRP}, an average travel-time T_{BRP} can be defined, over a set I of links i and a time frame τ:

$$T_{BRP} = \frac{\sum_i L_i}{V_{BRP}} \tag{2.6.11}$$

The technical implementation of the indicator was made by late 1986, and on January 1st, 1987, the systematic computation of VKT and BRP traffic indicators over the central zone, the first covered by the SURF system, began. In 1991, a four-year assessment report of SURF-managed central zone was published by the Direction de la Voirie [78], with figures based on the indicators. They had become the primary tool to assess both the system and the traffic conditions on the main arterials covered by the SURF system.

The BRP indicators being homogeneous either to a speed (V_{BRP}) or to a travel-time (T_{BRP}), they were quickly considered as "the" average speed in Paris. Nonetheless, its inventors, BONVALET and ROBIN-PRÉVALLÉE, had already warned of its limitations. As already stated, it is the result of a time average taken over "a short distance" ([30, p. 319]) dx (the length of the traffic loop), these short distances being assumed to summarize the traffic conditions over a whole area of influence (known as a link in the network model). The time average itself is taken over a time section "of moderate length τ [...] long-enough for many vehicles to pass" ([30, pp. 319–320]).

As a consequence, this indicator is not meant for travel-time predictions, as it averages "in the past": the value it returns at time τ results of a computation carried out from $t = 0$ to $t = \tau$.

The validation of the indicator was carried out against the two surveys, test cars and aerial, carried out to assess the SURF system [79]. BONVALET and ROBIN-PRÉVALLÉE raised the point that, when considering for a corridor the BRP speed against an aerial survey, the larger it was, the more accurate the indicator became. In fact, when averaging over a corridor, stability in flow (i.e., in an aerial view, stability in the number of vehicles) is more likely over a long length than a short one. The indicator would not reflect, or at least with some delay, sharp variations of traffic volumes. Moreover, sharp variations induce very spread out distributions, for which the mean alone is not relevant.

The BRP travel time is not an instantaneous travel time. Consider a corridor, made up of a set I of links i. The instantaneous travel-time $T(t)$ of a corridor at a given time t is the sum of the travel-times $T_i(t)$ of each of the links at the same time t:

$$T(t) = \sum_i T_i(t) \Leftrightarrow \frac{L}{\overline{\overline{V}}} = \sum_i \frac{L_i}{\overline{\overline{V_i}}} \tag{2.6.12}$$

$\overline{V}$ being the space-mean speed.

The BRP travel-time weights each link travel-time by its flow: in the indicator, the more trafficked links contribute more than the less trafficked ones. It translates its primary use: quantify a flow information, and not an individual one. In real-time, it is a travel-time meant for the traffic manager, and not the individual driver. That is in line with the data traffic loops collect: averaged informations on a traffic stream, and not individuals.

Starting in 1990, traffic statistics became part of broader statistical publications on "journeys", and not just traffic. An office of the Direction de la Voirie, the Observatoire des Déplacements à Paris, literally Observatory of Journeys in Paris, then began to publish its quarterly report [80], compiling statistics on traffic (the VKT and BRP indicators came later than the 1990 first issue), parking, traffic safety, mass transit.

In the end, despite its drawbacks and its original goal, the BRP indicator ended up being broadcasted in real-time on the City's traffic information system, launched in 1994. It is simply labeled "speed", so that the end-user takes it for the speed he will on average travel at. The spatial coverage of the BRP indicator gradually grew to cover almost all of Paris arterials, as more junctions were wired to the SURF system.

In the 1990s, an indicator originally designed for the traffic manager to supervise a traffic management system operation now served a variety of purposes:

Indicators Variations ($t_1 < t_2$)	$V(t_1) > V(t_2)$	$V(t_1) < V(t_2)$
$VKT_{norm}(t_1) > VKT_{norm}(t_2)$	Decreasing supply	Decreasing demand
$VKT_{norm}(t_1) < VKT_{norm}(t_2)$	Increasing demand	Increasing supply

Table 2.2 – Interpretation of the (VKT_{norm}, V_{BRP}) pair of indicators

- supervising the traffic conditions on Paris arterials: an indicator known in French as Tout Paris Intra-Muros (TPIM), was elaborated and started being transmitted on a weekly basis by the traffic management center to its head of staff;
- giving a speed and travel-time information to road users;
- feeding in traffic models, the BRP replacing test-car runs campaigns;
- assessing major works and projects impacting the traffic.

In its interpretation, the BRP speed has been used in relation with the normalized VKT_{norm}. VKT_{norm} can be seen as a virtual sensor on a virtual 1 km long section summarizing the traffic volume carried by the entire network. The BRP speed V_{BRP} is the quality of service to the corresponding volume. Beyond the absolute values of both indicators, both the traffic manager and the politicians paid attention to the relative gap between two periods: by how much percent had the VKT or BRP speed varied? Table 2.2 shows how the indicators variations were meant to be interpreted. It followed the classic interpration of the $q = f(k)$ function of the LWR model, with a supply and demand reasoning regarding the network (the supply) and the traffic (the demand).

What was perceived as a technical simplicity of the 1980s - relying on fixed traffic sensors - ended up being a main weakness of the indicator, along with its empirical and theoretical foundations. At the corridor level, a failing flow sensor can wreck the entire computation (especially if there is only one traffic count station for the entire corridor). A failing occupancy sensor means that several hundred meters of roadway fall into the unknown in terms of traffic conditions. At the network scale, these failures quickly add up and impede the quality of the indicator. A rule-of-thumb is that below 80 % of general sensor availability, care must be taken with the indicators. Moreover, variations become hard to interpret when the perimeter covered by the working traffic sensors changes. Failures can occur for a variety of reasons: obsolete hardware and construction works are the two main reasons. The maintenance workforce required to maintain a level of availability of the traffic sensors quickly became out of reach. Financially, funding cuts impeded the ability to restore broken traffic loops with the increase of road works (urban projects, but also massive renewal of underground infrastructure: metro stations, water, district heating, sewers, power). Moreover, the pace could probably not have been reasonably followed even if funding had been available.

The $TPIM$ indicator is shown on Figure 2.5, Figure 2.6 and Figure 2.7 and Figure 2.8. The $TPIM$ indicator allows to discuss the traffic conditions on Paris TPIM arterial network since January 2001. January 2001 marks a turning point on the political orientations regarding the private car. In the 1990s the traffic volumes in Paris stabilized, and the first traffic calming measures were taken over some zones labeled “quartiers tranquilles”, “quiet areas”. In 2001, the election of a new Left majority, backed by the Ecologist party, launched a massive campaign to reduce the car traffic within Paris. In terms of traffic engineering, this translated into two aspects: the reduction of roadway capacity (extended bus lanes, cycling paths, closure of roads) and the lowering of the speed limit (30 km.h^{-1} zones). The detail of these policies has been extensively studied, and the reader will find detailed account of the political decision making process in the literature. Among it, the Berlin-Paris cross-comparison by Fleury [81] shows how environmental issues are related to public spaces policies, mainly considering streets and squares, on which the traffic evolves. Changing public spaces is a way to implement environmental policies. Godillon [82] investigates speed limit policies in Paris, focusing on the gradual extension of the 30 km.h^{-1} limit over the City since the 1990s: she shows that the arguments brought forward by those supporting or fighting the measures must all be taken with care, given the complexity of both the urban environment and of the physics of traffic. Both in Fleury and Godillon, and in other works on traffic in Paris, the $TPIM$ indicator is used to quantify the evolution of speed and traffic volume in Paris. In 2001, the political program was to decrease the traffic demand (decreasing the VKT) while keeping the same network performance (maintain the BRP speed constant).

The computations are typically made over business days on the 07:00 to 21:00 time frame.

Figure 2.9 shows the theoretical length vs. the available length of arterials[15] included in the $TPIM$ network, from 2001 to 2017. Network-wise, 2001 marks the end of the major extension campaigns of the SURF system: as a consequence, no mew major arterials were equipped with traffic sensors[16]. The $TPIM$ theoretical length (that is, the total length of arterials that are equipped with traffic sensors) remained somewhat stable: it increased from a theoretical length of 312 km in 2001 to 367 km in 2017, an increase of around 17 %. This increase is mainly the result of the progressive inclusion of arterials (with a major update in 2014) that had not been previously integrated into the $TPIM$ network or were equipped with sensors in 2000s. The available length is the total length of corridors for which at least one flow sensor works (if no flow sensor works on a corridor, neither the VKT nor the BRP speed can be computed, as flow is an input to both of them). The plot shows how difficult it has become to maintain a proper coverage of the TPIM network with working sensors. The 2004-2007 period was impacted by major roadworks as some arterials were being rearranged for bus and tram lines. After a stabilization in 2007-2009, funding cuts linked with the financial crisis, along with the intensification of maintenance works on underground networks, caused a sharp drop in sensors availability that was never restored. The jump in 2014, along the major extension of the TPIM network of the 2001-2014 period, is only caused by the fact that the additional corridors added showed a nearly 100 % availability of their traffic sensors[17].

Figure 2.5 shows the normalized VKT indicator, and Figure 2.6 the BRP speed indicator, in their monthly and yearly evolutions from 2001 to 2017. It shows the superposition of two variations components that make up the TPIM evolution. The first component is the seasonal variation: in June, the year-high volume associated with the year-low speed (following Table 2.2, this is an increasing demand), followed by the year-low volume in August, associated with year-high speed (decreasing demand), the same situation being repeated in January, in lower proportions. The seasonal pattern is repeated every year. The second component is the general trend, which translates the overall network performance through time. From 2001 to 2017, the general trend clearly decreases: the traffic volume decreases from 1225 veh.km/1 km in 2001 to 802 veh.km/1 km in 2017, i.e. an over 33 % drop in sixteen years, whereas at the same time the BRP speed drops by 12 % from 16.6 km.h^{-1} to 14.5 km.h^{-1}. Note the actual values do not necessarily have a meaning, although they have, as previously stated, been taken as "Inner Paris

[15]Oriented graph: a two-way arterial counts double in terms of length.

[16]Among other arterials, the boulevard des Invalides is the major addition of the 2000s, along with other arterials: it was wired to the SURF system and equipped with traffic sensors in 2005, for the upgrade, with signals preemption, of the major bus line that travels on it.

[17]The 2014 addition was carried out by the author, in a general review of the traffic statistics based on the system's data.

average speed". The general trend thus translates, following Table 2.2, a decreasing supply and worsening traffic conditions. This in contradiction with the political will of the 2001-2014 period, which aimed at reducing the volume while keeping a constant speed. The decrease was sharper for the 2001-2008 period (first mandate of Mayor Bertrand Delanoë, with many traffic-related projects) for the 2008-2013 period. In 2013, the closure of the Voie Express Rive Gauche, Left bank expressway, turned into a pedestrian promenade, significantly reduced available capacity in the central zone. With some stabilization in 2015-2016, in late 2016, the closure of the Voie Express Rive Droite, Right bank expressway, in the central zone, further reduced the capacity and triggered a lower volume (increased congestion, as the BRP speed also dropped).

The interpretation of the $TPIM$ indicator must nonetheless be put into perspective. Figure 2.7 shows the normalized VKT and the BRP speeds indexed on January 2001 values, in parallel with sensors availability. Sensors availability is the percentage of working sensors on the available TPIM network (corridors with at least one traffic flow measure available), multiplied by the length ratio of available over theoretical TPIM networks (as illustrated by Figure 2.9). From 2001 to 2017, it shows a sharp decrease in availability, from nearly 90 % in the 2001-2004 and 2007-2008 periods (the 2005-2007 period saw major construction, hence the temporary unavailability of traffic sensors which were then restored upon completion of the works) to about 65 % today. The BRP speed started to decrease continuously as the availability of sensors dove. Although the VKT keeps decreasing even when the availability bounced back in 2007-2008, care must be taken for both indicators passed 2011, when the availability dropped below 70 % (the rule-of-thumb threshold being 80 %, passed below in 2010).

The loop-based $TPIM$ indicator offers a continuous insight of traffic performance on Paris arterials for over fifteen years, but the fact that it relied on an extensive, hardly maintained hardware infrastructure gradually caused its demise. It is still in use as of 2017, but in need of a replacements.

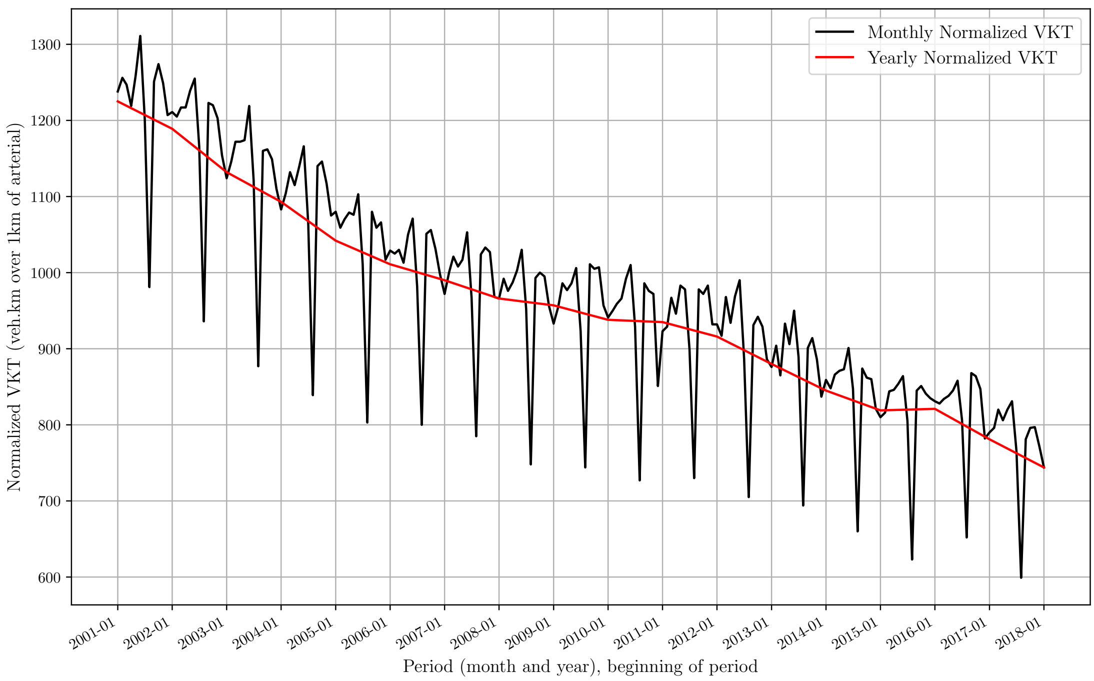

Figure 2.5 – Normalized VKT over TPIM arterial network. Monthly and yearly averages, business days, 07:00-21:00.

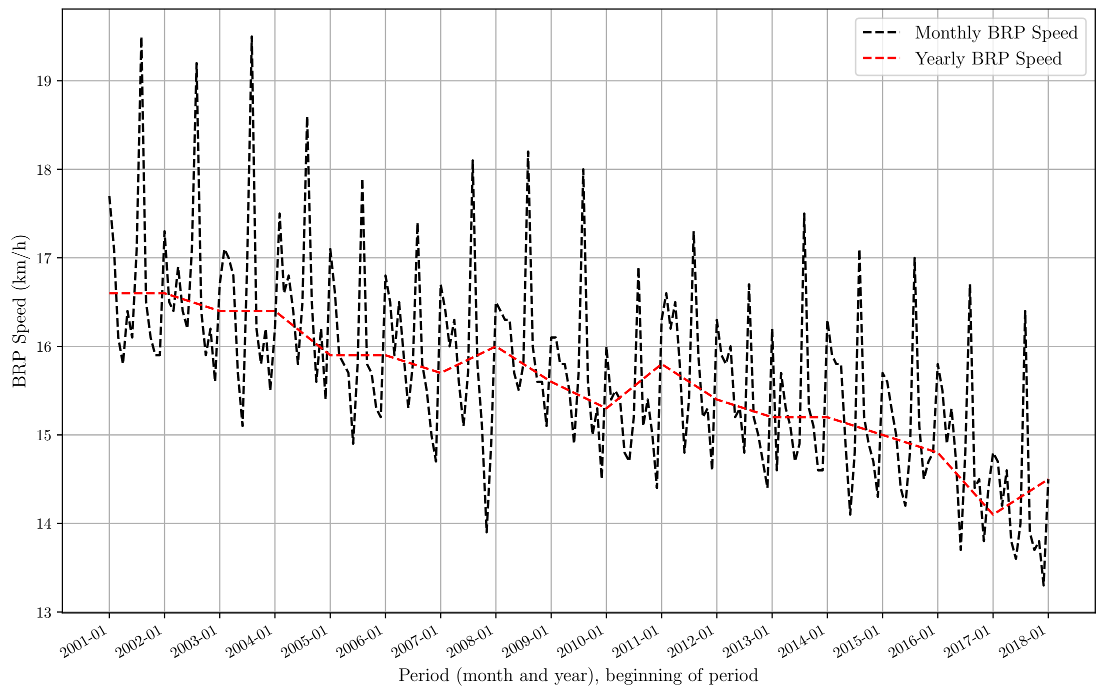

Figure 2.6 – BRP speed over TPIM arterial network. Monthly and yearly averages, business days, 07:00-21:00.

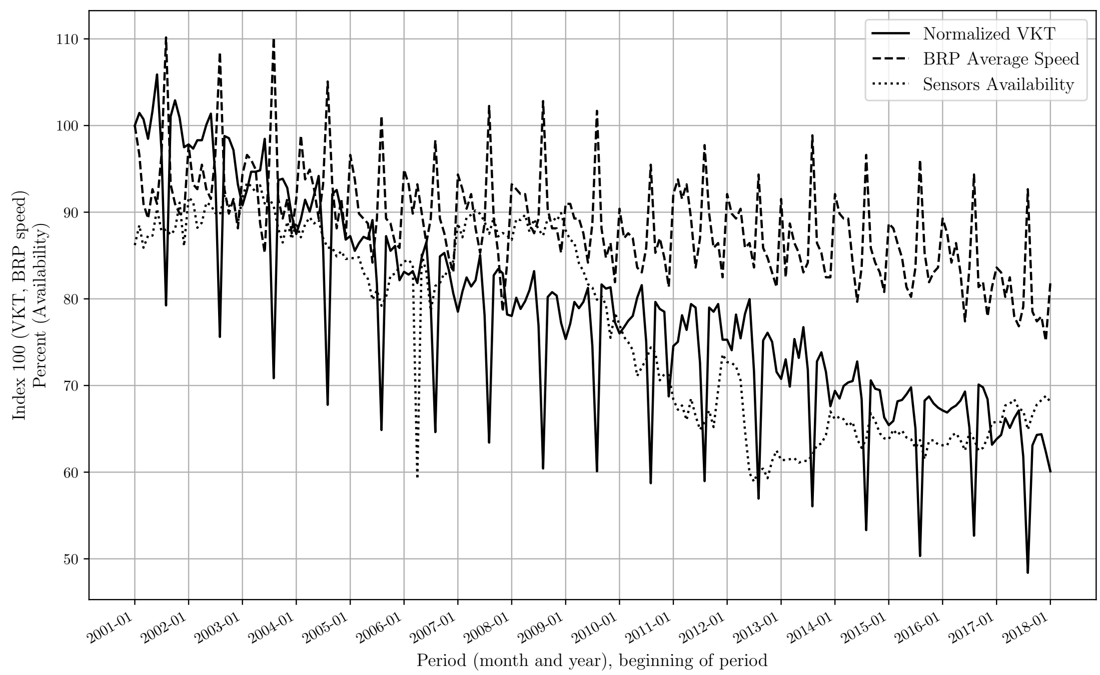

Figure 2.7 – Normalized VKT and BRP Speed over TPIM arterial network. Monthly averages, business days, 07:00-21:00. Indexed on January 2001 values. Sensors availability, in %.

Paris case shows that the road network was quickly thought like a system to be managed, and not only an urban space. Traffic data answered the need for quantification of "what was on the streets", and played a key role in defining policies to deal with the traffic. These policies were at first oriented toward road building, and then gradually switched to an "information" infrastructure, paralleling the main arterials of the road network, and used by the traffic lights management

Figure 2.8 – Normalized VKT and BRP Speed over TPIM arterial network. Monthly averages, business days, 07:00-21:00. Indexed on January 2001 values. Sensors availability, in %.

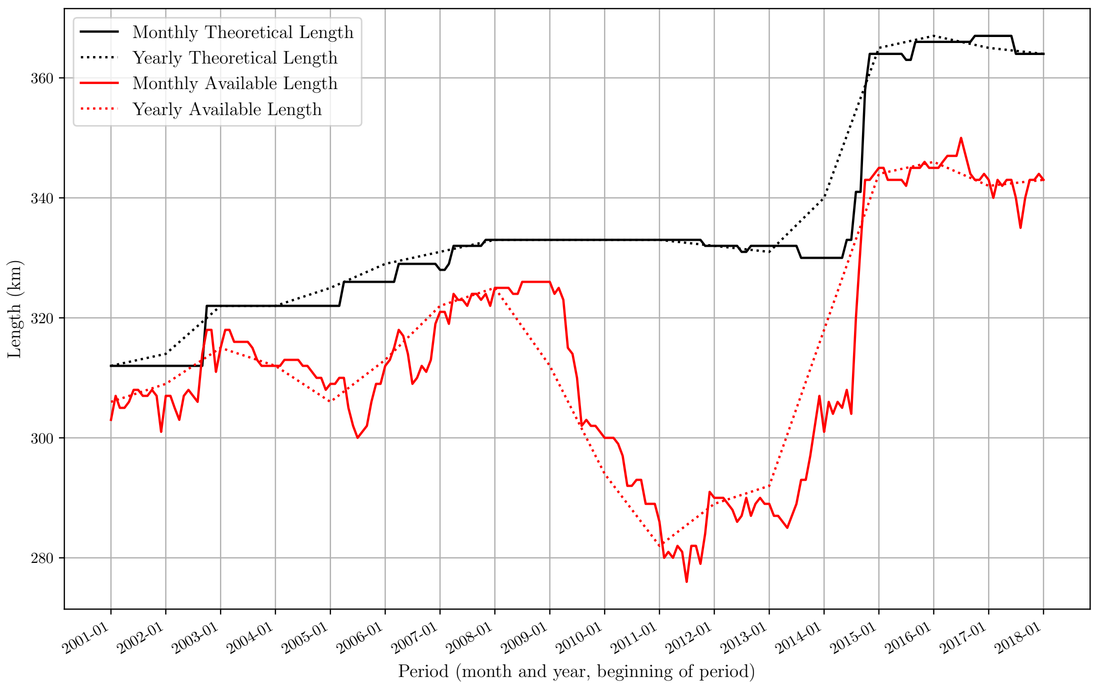

Figure 2.9 – Theoretical and available length of TPIM arterial network. Monthly and yearly averages, business days, 07:00-21:00.

system. A new network, parallel to the road network, was thus created and gradually expanded, to monitor it real-time, thanks to thousands of traffic loops. The sensors not only served the traffic lights actuation algorithms: they were installed for statistical means. They yielded data allowing real-time computation of vehicle kilometers traveled and average speed estimate indicators that have since then played a key role in assessing traffic-related and street-related policies in Paris.

Nonetheless, the complexity and large spatial coverage of this network of sensors in some way causes its gradual dismal, under various factors. These include a rising number of stakeholders working on the streets (telecom, energy, transport companies), aging assets in need of renewal, and increased safety procedures to restore sensors.

2.7 Conclusion

Road maintenance and improvement were, from the start of traffic engineering in the early XXth century, the key motivations behind traffic data collection. As a link was drawn by road authorities between road condition and the volume of traffic, traffic count became the first of traffic data to be methodically collected.

Rising traffic demand yielded an additional question: how many cars could a highway cope with? Congestion became an issue, and capacity gradually a variable to estimate it and quantify the needed improvements on the infrastructure.

Road and traffic research is institutionalized, in the line of the Eno Foundation, and multiple experiments are carried out to observe and quantify traffic. Works by Johnson, followed by Adams and Greenshields, yield first definitions of vehicle gap and headways, velocity, density, volume, although the terminology of the time is not necessarily the same than today's. In an effort to quantify and predict congestion, first investigations are carried out on the relationship between velocity and density, velocity and volume. The first theoretical background is given by the theory of probability.

Two means of observing traffic were experimented: ground-based spot observations and aerial observation. Both of them yielded their set of definitions, and already raised the dilemma posed by these two methods. The road authority wants to have thorough knowledge both in space and time of the traffic on its network.

Spot surveys are "cheap" but only provide data at a specific location over periods of time. Aerial surveys provide much more extensive spatial information, but at great cost and only at a specific time.

These works aimed at understanding and quantifying traffic for road maintenance and planning reasons. Theory could help plan future behaviors without necessarily requiring extensive measurement campaigns that were tedious and expensive.

During the two decades that followed the war, from the 1940s to the 1960s, much of today's traffic variables were precisely defined, based on the experience gathered from the early twentieth century and the refinement of observational techniques.

All the traffic engineering manuals shared the common goal of offering a comprehensive review of existing principles and practices regarding traffic engineering. They concentrate on operational variables, for which we can already perceive two overlapping categories. The first one includes variables relative to the traffic stream or traffic flow, with the speed, the volume and the capacity. The second one covers the network performance or efficiency, with the travel-time (and its associated journey speed or over-all speed) and the volume considered within origin-destination studies.

Beyond the definitions these manuals provide, they also offer insight on the methodologies available at the time, but also on the motivations standing behind this whole branch of engineering. These range from maintenance to the issues of safety, congestion which is seen as something meant to be overcome, to more explicitly the performance of the network, through its efficiency.

Sign of their usefulness, the stability of these publications is worth noting, as most of these books have been repeatedly updated until today.

Traffic flow variables are: flow, concentration, speed. These are brought up as the analogy between traffic flow and the fluid theory, already felt in the 1930s, is formalized. The definition of the variables remains closely associated to how they are measured, schematically either from a spot on the road (Eulerian observer) or by a moving observer (Lagrangian observer).

They are defined over a rather imprecise scale by WARDROP, and then by LIGHTHILL and WHITHAM: EDIE proposed a generalization of the definitions over a random space-time area, which somehow solved the problem at least analytically. Nonetheless, the minimum time duration of spot observations remains a question.

The average issue (either in space or time) is closely linked to method of data collection (spot observation or from the air), as identified by the authors. Time-mean speed is the easiest to collect at a point on the road, whereas the meaningful speed for drivers is the space-mean speed, which is the reciprocal of journey time.

The relationship between flow, concentration and speed becomes known as the fundamental diagram, and is meant to summarize the resulting interaction between demand (drivers) and the supply (infrastructure), which is traffic.

The operational needs calling for global indicators, such as vehicle kilometers traveled and travel-times, were already identified in the early days.

A compromise with the available technology had to be found.

This is true for vehicle kilometers traveled estimates. It relies on traffic counts, which are "easier" to collect than any other traffic data. It also depends on the average length of trips, which is much harder to catch.

Travel-time is a step further in complexity: various and more or less complex sampling method were set up, but that would only give partial results at great cost. Studies of travel-time however raised remarks on their distributions that are still valid today.

Paris case shows that the road network was quickly thought like a system to be managed, and not only an urban space. Traffic data answered the need for quantification of "what was on the streets", and played a key role in defining policies to deal with the traffic. These policies were at first oriented toward road building, and then gradually switched to an "information" infrastructure, paralleling the main arterials of the road network, and used by the traffic lights management system. A new network, parallel to the road network, was thus created and gradually expanded, to monitor it real-time, thanks to thousands of traffic loops. The sensors not only served the traffic lights actuation algorithms: they were installed for statistical means. They yielded data allowing real-time computation of vehicle kilometers traveled and average speed estimate indicators that have since then played a key role in assessing traffic-related and street-related policies in Paris.

Nonetheless, the complexity and large spatial coverage of this network of sensors in some way causes its gradual dismal, under various factors. These include a rising number of stakeholders working on the streets (telecom, energy, transport companies), aging assets in need of renewal, and increased safety procedures for the roadworks required to restore sensors.

Chapter 3

The evolving relationship between drivers and road authorities: occasional, centralized, then shared. Paris and Lyon cases, from the 1920s onward.

Sitting behind his steering wheel, interacting with his vehicle's mechanics, the driver journeys through the city, making permanent compromises between his will of movement and his surroundings. From the beginning of motor traffic in the early 1900s, conflicts between motorists and these "predating" users quickly rose as did the number of motorized vehicles.

The body in charge of the road network can be generically referred to as the road authority [1].

The road authority holds three main overlapping missions. Its first mission, the most crucial, is ensuring the safety of the various users on its roads. Its second mission is handling the traffic. Its third mission is on a longer term than the two others: it involves planning, designing and implementing the layouts that serve the policies to be enforced. The authorities in charge have tried to solve the issues caused by the growing traffic through various regulations. Therefore, informing drivers of the regulations in place became crucial both for the authorities and the drivers. Meanwhile, traffic engineers soon became aware of the complexity of behavior-control, and thus devised new means to integrate the "driver-car unit" within the environment [83].

From signs to mobile applications and traffic lights, directing the driver is the aim of numerous systems, especially in an urban setting where both congestion and safety issues stress more than anywhere else the need to control traffic. The regulations fall into two categories. The first category of regulations consists in prescriptions, mostly defining one-way streets and authorized standing and parking locations. The second category is the signposting norms, which are essentially addressed to occasional drivers, orienting them towards the city's landmarks and main parking lots. Signposting has evolved through time, but its main principles have remained the same from the 1920s until today. The 1968 Vienna Convention on Road Signs and Signals established, for ratifying countries (which includes most of Europe), common grounds on signs.

At first infrastructure managers, road authorities gradually become "flow managers", and

[1] The road authority will be referred to as "authority" or "authorities", unless more precision is needed.

then “journey managers”. From the start they hold a growing interest for the car-driver unit. Technological changes play a key role, as new devices are progressively integrated into road authorities traffic management policies, which go beyond infrastructure-building. Meanwhile, they also allow the private companies to be increasingly involved in traffic management, both at the “flow” and “journey” scales, mainly because of the rise of commercial car-base and user-based units, from the 1990s onward. This increasingly questions the public sector’s monopoly in the field of traffic management.

This analysis is anchored on two disciplinary fields, history and traffic engineering, which both consider the same object: the way road authorities consider the car-driver unit and how they communicate with it. Drivers’ information itself is composite: it holds both a geographical aspect (main locations, routes) and a regulatory aspect (signed speed limits, prohibitions, etc.). At first, drivers’ information consisted in punctual devices responding to specific situations, and has subsequently gradually been diversified and extended across the cities, now becoming an important part of global traffic management policies that may include other modes of transport. Drivers’ information is of growing importance within urban traffic management systems, which evolve through time within a moving political and technological context. Nevertheless, drivers’ information systems are more the result of the successive stratification of past practices than complete replacements of previous systems.

This work is part of the broader history of traffic management policies, which have been thoroughly investigated since the 1990s, mostly by analyzing the urban upheaval caused by mass-motoring in the twentieth century. For instance, FLONNEAU studies the car-induced transformations of Paris town planning [66]. NORTON investigates the political fights between the stakeholders of the different transport modes for the control of the street flow capacity [84]. Few of these studies specifically focus on signaling infrastructures as tools of traffic management. The only French book on road signs draws their history, but only skims through local policies [85], while most historical studies focus on the inception of these devices, like BUITER and STAAL’s on first Dutch traffic signals [86] or SESSIONS’ on the inception of “traffic devices” [2]. Other transport historians have studied signaling history through national-scale comparisons, like MOM [87] or MCSHANE [83].

The present study aims at enhancing these national-scale analyses in two ways, from the first city-wide schemes of the 1920s to the early 2010s. The first point is to assess the autonomy of local bodies on the decision-making process for traffic-related devices, along with the local political stakes, while dealing with an increasing number of national norms and regulations. The second point is to adopt a long-term perspective, which allows to stand back on the evolution of the technical devices, by showing their interdependence with the quick-changing traffic policies they were designed to serve. The user position is worth an historical perspective: a key issue of signaling devices is to communicate to the user (here, the car driver) information stemming from technical systems on which he has no control. This also gives a new insight on the history of car infrastructure-building and urban transport policies: it shows that these gradually take a wider account of the uses, by attempting to route individual trips, whenever the technical innovations allow to reach the individuals rather than a “flow”. The field of transportation and mobility history increasingly looks upon the users’ role within the history of technological devices, as shown by recent studies on road and traffic safety [88] and congestion [89]. It is relevant to focus, as the present study does, on drivers’ information systems in a urban setting. Information involves many stakeholders, among which the traditional urban roads authorities: municipal engineers, Service Ordinaire des Ponts et Chaussées State engineers, the latter becoming Direction Départementale de l’Equipement in 1967 [90]. It also includes the private sector which have shown early interest in the whereabouts of drivers, along or competing with road authorities, from privately-funded roadsigns to private traffic data.

Drivers' information systems visible on the streets reflect traffic management policies. We focus on the two biggest cities in France, Lyon and Paris, whose transportation networks' history is well documented [66, 91]. This study mainly relies on public archives, mostly municipal departments files and traffic engineers' studies and reports. Comparing these two cities allows to assess the role played by the local geographical and political contexts on the inception of devices meant to answer similar traffic-related problems from the 1920s to the 2000s. For instance, Paris is the capital of France, and hence holds a specific status, whereas Lyon is a key transit node: these two local characteristics significantly influence the traffic devices devised. Moreover, it could be expected that Paris, which has encountered early traffic congestion problems, had acted as a reference to other French cities. We will nonetheless show that other major cities, like Lyon, have in fact followed their own paths.

This study is anchored in the aforementioned broader national and international historical context of motor traffic in urban environments. Focusing on two main French cities, Paris and Lyon, the study shows the winding evolution of the relationship between drivers and road authorities. This evolution is fueled by both technical and political changes: this can be broken down into three great periods.

From the 1920s to the 1950s-1960s, the road authority both manages the infrastructure and the traffic as one same homogeneous set. The driver is rather "free" and his relationship with the authority quite loose, limited to the road and the signs. The said relationship can also be shared with private companies who provide some signs on behalf of the authorities.

Around 1970, the driver-authority relationship changes radically with the overall expansion of real-time traffic data collection infrastructure, the result of the industrialization of existing traffic sensing processes. A whole new information network (cables, sensors) is then built along the main roads. The road authority gains a real "traffic management" function. An exclusive relationship links the traffic management entity and the driver. The authority sends information to a flow (and not individuals) and the driver (as an individual) generates information through the road and associated information infrastructures, that only send "flow" variables to the authority.

Around the mid-1980s, the centralized systems are mature and traffic information broadcasting circuits are in place. Meanwhile, the exclusivity of the link between the driver and the authority yields ground. Information intermediaries appear between the authorities and the driver, aggregating data from different authorities and broadcasting them to their clients. These private service providers are at first exclusively based on public data. Nonetheless, as drivers (or their vehicles) themselves start to generate data on their own journeys, and as public infrastructure begins to decline, private intermediaries then design an individualized link with each of their clients.

3.1 1920s to the 1950s: informing drivers, a back-burner issue for road authorities

Drivers' information becomes a serious concern starting in the 1920s, as car traffic causes tangible congestion and safety issues. Nonetheless, road authorities do not launch information-dedicated policies. Drivers' information relies on static signs, which are considered as complementary devices serving traffic management policies. The driver is mostly seen as a person taking occasional trips in the city, thus in need of guidance on a road network not really designed for him. The driver first needs to know which way he needs to drive (left-hand or right-hand side of the road, one-way streets, ...) and where he can park his vehicle. He also needs to know how to get to his destination, and perhaps have his curiosity stirred for a specific location he did not initially consider. This image of the "occasional driver" on which policies focus is one of the factors that allowed the private sector to initiate the first signaling schemes, which were then backed by the public authorities.

3.1.1 Public and private devices for occasional drivers

Signposting is older than motoring (cf. Figure 3.1) [92]. Nevertheless, it is increasingly needed starting in the 1920s, mostly for car drivers. Information to street users, from pedestrians to drivers, is mainly done through signs indicating the main arterials and locations. New thoughts are given on their implementation from the 1920s onward, to indicate one-way streets that have been set up in numerous French towns including Lyon and Paris, to identify stops on the developing surface transit networks, or to show main locations and routes to foreign (understood here as not from the city) visitors. Automobile signs are promoted by drivers' associations, like the Automobile-Club and the Touring-Club de France, and by car-related manufacturers like Michelin or Citroën. The car industry is heavily involved in signs production, which it then proposes budget-tight road authorities to implement both in urban areas and in the countryside.

The rise of auto touring means that Lyon and Paris, like many of their European counterparts, receive more and more foreign visitors not necessarily familiar with its spatial layout and driving regulations. Lyon has a greater stake in about transit traffic than Paris. Nonetheless, the same process for directional signposting schemes can be observed in both cities : a proposal by Citroën, accepted by municipalities without any associated funding.

The regulations are increasingly complex from the 1920s onward, as the first ones are voted by the municipalities (in 1910 for Paris, in 1926 for Lyon). For example, one-way streets can be disorienting for foreign drivers, leading them to commit unforeseeable offences, which in return will both alter their experience of the city and cause incidents impeding local traffic. The first comprehensive signposting scheme in Lyon was proposed by the Citroën Company, which plans 97 enamel signs to be put on municipal streetlight poles to indicate both the downtown and the main cities that can be reached from Lyon's main arterials. This scheme was meant to answer "Lyon's signposting problems" ("Problèmes de signalisation à Lyon") pointed by the President of the Tourist information office. It was examined during a meeting which gathered State, Département and municipal engineers, with representatives from the Touring-Club de France and the Automobile-Club du Rhône. They all agreed on the need of providing a better guidance to car drivers, but public funding for signposting schemes remained quite low [93]. It was suggested that the cost of laying the enamel signs would be shared between the Ponts et Chaussées Administration, authority in charge of the to-be-signposted roads, and the Chambre d'Industrie Touristique de Lyon (Chamber of Tourism Industry of Lyon), part of the Chambre de Commerce et d'Industrie de Lyon (Chamber of Commerce and Industry of Lyon). This shows how touristic issues prevailed on street traffic management at the time.

In the 1930s, drivers' information main goal was traffic safety, especially to avoid the often deadly accidents between cars and pedestrians, which were the most frequent [94]. This aspect had already been considered in the past years: in 1912 the first traffic booth was installed in Paris, at the intersection of boulevard Montmartre and rue du Faubourg-Montmartre. Paris distinguishes itself from other French cities by giving the earliest thoughts on traffic management The 1910 Rapport Massard for the City of Paris Municipal Council promoted signposting infrastructures as a tool for improving traffic flow [66].

Congestion also became a new aspect of drivers' information, especially in the 1930s. Congestion predated the automobile, mostly in downtown areas for Paris and Lyon, but became an increasing concern as motorized traffic volumes grew.

3.1.2 Towards signing policies to fight congestion

The lack of information was often raised as a major factor in the disturbances caused by traffic, whereas the car still held a low modal share in surface, or "on-street", transport. Drivers' information thus became more comprehensive, with policies then covering the entire city. Indicating to the occasional or out-of-town drivers the available parking lots, the main sights, and administrative and business locations held a growing importance. This translated into comprehensive signposting schemes in both Paris and Lyon in the early 1930s, heavily drawn by drivers and tourism unions.

The first Lyon signposting scheme, proposed to the municipal authorities in 1931 and implemented in 1934, translated how priority was given to tourists, whereas the efficiency of signs against congestion was already known of. For its designer, this scheme held three purposes. Its first purpose was to help the driver in ending his stay in the town, by indicating him how to leave the city. The second purpose was to "easily find the Bellecour Square, Lyon's most central location". The third was to "ease the flow of drivers that do not want to stop in Lyon, by diverting them away from the congested central zone" [93]. The strain between the diverging interests of tourism-friendly and congestion-fighting policies can be clearly felt. Tourism and the need to attract people downtown seemed to prevail over important issues raised by transit routes crossing central Lyon.

In Paris, congestion issues prevailed over other considerations, as they were considered more urgent than in Lyon. Paris was an early-adopter of technical innovations in signaling, like the deployment, starting in 1923, of traffic lights at several key downtown intersections. In Lyon, the first traffic light was only installed in 1937, and they did not enter general use there until the 1960s. These city-wide car-oriented schemes were part of broader transport policy changes, in which cars prevailed over other modes of surface transport, mostly tramways. Paris was one of the first major European cities to undertake the systematic discontinuation of its tram system between 1927 and 1938, first downtown and then gradually into the suburbs [95]. Congestion was the main argument raised to justify the transition from rail-based to bus-based transit lines. In Lyon, the first replacement of trams by buses occurred in 1926, while trams ran until 1957. The process was slower since congestion issues were less staggering than in Paris, but also because of the financial problems of the Lyon's transit companies in the 1930s.

This first era of drivers' information in cities is marked by the low interest shown by road authorities in this matter. They primarily consider the infrastructural aspect of traffic, and leave drivers' information as a tourism issue, to be assumed for a part by private companies. This era characterized by the implementation on the streets of technically simple objects, signs, meant to give regulatory and geographical information to motorists. On this aspect, Paris and Lyon basically follow the same path, Lyon adopting a slightly slower pace than Paris. Nevertheless, the main fundamentals of drivers' information policies still in place today were then settled: signposting systems covering the entire city, and technical innovations devoted or adapted to car traffic. Starting in the 1950s, a breaking point is reached: the driver is then less and less considered as an individual by the various authorities, but more as a particle within a flow of vehicles.

3.2 1950s-1980s: drivers in a stream

The 1950s-1980s period was marked by the inception of devices allowing to broadcast information to the stream of traffic. The devices were seen as the means through which traffic management policies were implemented. From the authorities' perspective, deeply influenced by American traffic engineering practices, the individual car driver was now part of a traffic flow [12]: the authorities' mission was to guide and distribute the flow across the existing network, while at the same time being involved in the design and construction of new infrastructures. During this period, Lyon and Paris relied on the same means: traffic-actuated synchronized signals, ordering the network between local streets and main crosstown and bypass arterials and expressways. Lyon implemented some of the available devices later than Paris, showing the need to adapt these to local needs.

3.2.1 Traffic flow information as a key traffic management tool for roads authorities

From the 1950s onwards, information became the keystone of traffic management policies: this both included the information stemming from the data collected by the authorities (through its traffic sensors) and the information transmitted to the traffic flow.

Starting in the 1930s, but essentially after the Second World War, new street layouts favored the car over all other surface transport modes, be it in Paris or Lyon. Authorities applied to urban roads rules, arrangements and assets originally designed for interurban roads planning: traffic segregation, widened and paved roadways. Despite this, drivers were not the target of information systems as individuals, but as part of a broader traffic flow traveling on a network that needed to be decongested. Figure 3.3 illustrates this fact: an arrow signal allows through movement at the signalized junction for part of the red-light time, thus increasing traffic flow capacity across the junction, but reducing pedestrian crossing time. These layouts, greatly inspired by American traffic engineers and adopted by the Ecole des Ponts et Chaussées, took little account of the diverse street use habits and of its various users [12].

From the 1950s onward, within drivers' information policies, congestion-fighting seemed to prevail over all other considerations like safety, both in Lyon and Paris. Congestion was scarcely observed in the 1920s and 1930s "scientific" traffic studies [17, 24], but it became important in the 1940s in America [23], followed by Europe once the war had ended. The development of drivers' information systems must be put into perspective with the simultaneous generalization of traffic studies, starting in France in the 1950s with American methodology and devices. Routes that needed signposting were the ones that mixed both main interurban routes and local journeys. Becoming the urban network's core, these arterials attracted more traffic and ended up being the most congested.

Drivers' information evolved after the war into a more global approach considering flows instead of individuals: this then became known as traffic management policies (such terminology appears in France in the 1950s) [96]. Drivers' information systems left their very local, nearly experimental approaches, for a broader, citywide globalized approach. Paris pioneered the field, but Lyon, although influenced by the Parisian decisions, adopted its own model. These policies relied on two mainstays. The first was infrastructure, through major urban motorway schemes, defined both at State and local levels. The second pillar was the widespread implementation of traffic lights across main arterials and their coordination through "green waves". In Paris this was done as early as the late 1940s: the first traffic light coordination system was installed from

1948 onwards for the city center. These systems were installed inside control rooms, with at the center the synoptic of the monitored junctions: Figure 3.2 shows the Poste Maillot control room in 1956. Lyon followed Paris a few years behind, with a traffic lights deployment policy in the 1960s, followed by their coordination in the 1970s. This more progressive approach in Lyon can be explained by two factors: the lower traffic volumes than in Paris, and the massive infrastructure policy brought forward by Louis Pradel, the mayor of the time, which favored grade-separation over traffic lights for busy intersections, and the construction of a motorway through the city center [97].

These drivers' information systems took growing room within the cityscape and transport policies, as an answer to growing issues caused by traffic increase. Infrastructure building policies through the urban cores mostly stalled with the oil crisis in 1973. Important changes in the governance of transport followed, both in Paris and Lyon.

3.2.2 Traffic flow at the core of coordinated policies

Drivers' information systems were also important for the coordination of administrative actors and their traffic management policies. Authorities aimed at a coordinated management between State-managed roads and municipal roads: for example, the State, at the national level, organized traffic information with the Gendarmerie in 1966-1968, which paved the way to the Centre National d'Information Routière (CNIR, National Center for Road Traffic Information) in 1969 [98]. The Directions Départementales de l'Equipement (DDE) linked these State structures with local administrations, to which majors parts of the urban State road network (excluding motorways) were transferred, starting in 1973.

The coordination between the different drivers' information parties varied. Debates were centered on the transition issue between local streets and main interurban and urban arterials and expressways. The Paris case remains peculiar as the State kept complete authority over most of its arterials. A main arterial network existed there since the 1950s, and remained at the core of the successive traffic plans, including the 1976 one. Starting in 1976, the associated signposting scheme was implemented with backlit directional signs. These signs "allow[ed] to carry and guide drivers over a network covering the city and highlighting major traffic nodes" [99]. The Paris ringway scheme, or Boulevard Périphérique, its first segment opening in 1960, introduced a new kind of road within the city's limit, the urban expressway, nonetheless referred to as a "Boulevard". On the ringway and the outermost ring of boulevards that parallels it (Boulevards des Maréchaux), a specific signposting and traffic management scheme, called CORRIDOR, was implemented.

In Lyon, the city's ringway is much older and started off at its inauguration in 1934 as an at-grade urban road, the Boulevard Laurent Bonnevay. It was excluded from the first signposting schemes of the 1930s. After the war, it became a central part of the network as it was gradually, from 1958 onward, turned into a grade-separated expressway, and thus included as a top-priority route within subsequent signposting schemes. Classified as a State highway, and then downgraded as a Département road, it nonetheless kept its expressway status and was therefore distinguished from the rest of the urban street network.

At last, users' information was one of the first means to unify transport mode-based policies. Direction signs started to consider other modes, as the first multimodal policies are instated by all major French cities in the late 1970s. In Paris, the 1976 signposting scheme, complemented in 1985 by the Schéma directeur de la signalisation d'indication (Direction Signs Master Plan), was not only focused on car traffic, but also on standardizing pedestrian direction signs, pointing towards points of interest “whose access is sometimes difficult for pedestrians, mainly when coming from public transport stops or parking lots”. This master plan showed the growing concern for multimodality, and the decrease in automobile pressure: “it is mainly addressed to pedestrians with, when the situation calls for it, some complimentary signs for car drivers” [99]. This means it was now accepted that some locations within the city could not be directly reached by car.

Unlike Paris, Lyon’s signposting schemes took little account of multimodality issues: the signposting master plan was solely dedicated to cars, and did not take other modes into account. The plan launched in 1977 associated two schemes: the signposting of major arterials and junctions, and a centralized traffic management scheme based on traffic lights coordination [100]. These two combined schemes aimed at concentrating drivers onto main arterials, on which traffic lights management would guarantee free-flowing traffic. The only benefit to drivers would be the time gain obtained by diverting flows onto the larger roads. Lyon focused on cars until the 1990s. Centralized traffic management systems, which opened up the multimodality issues, were only set up almost twenty years after Paris, hence the associated questions had not been addressed until then.

Drivers’ information policies from the 1950s to the 1970s broke from previous 1920s and 1930s policies, both in Paris and Lyon. To fight congestion, traffic management prevailed over all other considerations. The prevailing flow orientation policies seems to fade already in the 1970s, with the axing of most urban infrastructure programs and the rise of information technologies (IT).

3.3 From the 1980s to nowadays: back to individual drivers

The 1980-1990 period marked a turning point in the transport management policies initiated in the 1960s in Lyon and Paris, among the other major French cities. Technological evolutions of drivers’ information systems allowed the road authority to more directly reach the drivers and to increasingly route them during their journeys. This backed the focus on individual journeys, part of broader multimodal policies, but did not bridge the coordination gaps between the different public stakeholders, that still all primarily serve their own purposes. This gave room to the rise of private actors, that have since 2000s increasingly relied on crowdsourced data. They have gradually become independent of the public authorities’ infrastructures, and therefore can give a comprehensive service and bridge the service gap for the drivers.

3.3.1 The central systems era: public monopoly over drivers

In the 1980s, information and communication technologies came along two simultaneous processes: one is the centralized management systems, the other is differentiated information feeds in line with the traffic manager’s concerns. These stirred towards dynamic real-time information, halfway between managing a traffic stream and considering the individual drivers part of it.

Real-time information primarily relied on Variable Message Signs (VMS) in major cities like Paris and Lyon, at first on the bypassing roads (ringways, etc.), and then extended on some major arterials. On the Paris ringway, following a static signs renewal campaign in the 1970s and early 1980s, in 1985 the southern section was equipped with Variable Message Signs (VMS). These first VMS then served several goals, among which to provide information on traffic conditions to the drivers more precisely than over the FM. Subsequently, a broader VMS deployment campaign along the entire ringway was launched, to warn drivers of maintenance works, incidents, and inform them on traffic conditions on the radial motorways interchanging with the ringway. In

Lyon, VMS deployment was planned in the early 1990s as part of the CORALY program, but was at first dedicated to transit traffic: only the urban motorways and expressways were equipped, with about thirty signs during the first phase [101]. This translated Lyon's policy to discriminate transit and local roads and streets, in line with predating policies.

Besides VMS, drivers' information was also broadcasted through FM radio stations and the first experimental onboard guidance systems, like Carminat on some Renault cars. Even though the range of available means for dynamic drivers' information broadcasting was widening, with the privatization of onboard broadcast circuits, road authorities remained at the root of all information and traffic data.

The INF-FLUX program, part of the CITIES experiment of the DRIVE/ATT European project, is a relevant example of these drivers' information systems, as Figure 3.4 shows [102]. Traffic information broadcasting within the CITIES experiment shows the administrative and technical layout of a system that only relied on public sensors and stakeholders. This meant that four distinct traffic management systems covering distinct sections of the Paris region road network had to be connected: IPER-REPER for Paris ringway, and SURF for Paris traffic lights and urban arterials, SIRIUS for the State-managed motorways and expressways, and PARCIVAL for the traffic lights and urban arterials of the Val de Marne Département. Private service providers were not included in the setup.

Both in Paris and Lyon, in the 1990s, the VMS became part of their respective comprehensive traffic policies, which triggered their deployment within the city. Before the late 1990s VMS remained rare outside the expressway network, mostly for esthetical reasons. In 1993 in Lyon, the parking lots dynamic signposting scheme's first goal was a "breathing city", meaning, according to its author, "reducing the interfering traffic generated by drivers looking for available parking spots". Seeking available parking spots, i.e. "prompting the driver to park his vehicle in a car park" (Figure 3.5), only came in second. Moreover, in both cities, the so-called "local" direction signs, static for the most part, were gradually being standardized and simplified, as the municipal administrations ensured that they were well integrated within the existing cityscape and street furnitures. This idea was widely shared among the urban road authorities of the major French towns. In Paris, for instance, the 1985 Direction Signs Master Plan stated, about the backlit direction signs implemented across the city, that the "the increase in the number of vehicles ha[d] caused an increase in the number of regulatory signs" and that "the growing complexity of the urban road network brought up the need for signposts for vehicles, as to reduce the time lost finding destinations and to keep traffic flowing." In Lyon, for instance, the new 1996 Signposting Master Plan was justified by the opening of new roads, the upcoming Local transport plan (Plan de déplacements urbains), and "restoring consistency among several historical layers of signposting schemes" through more explicit mentions [103].

The rise of information technologies changed traffic management policies in the 1970s and 1980s. Nonetheless, traffic information remained for the most part dedicated to the road authorities, whose aim is to set up and manage road capacity to facilitate at best drivers' journeys through maximizing the flow and lower global congestion across the network. The move towards onboard traffic information terminals only picked up in the late 1990s, while road authorities gave, through the spreading VMS infrastructure, even more numerous and precise information.

3.3.2 Drivers as probes: public and private conflicts

Traffic information shifts from traffic flow to drivers, or even more generally transport users, mainly under two trends. The first trend is the massive technical evolutions, which ease drivers' access to traffic information, integrating it into their car use habits. The second trend, deeply linked to the first one, is the shift in transport policies. Authorities now want to act on demand, as the available technologies now allow measuring its whereabouts: journey purpose, traffic dynamics, modal choice. Through these widespread onboard devices, private companies take their share in the relationship between road authorities and drivers.

The first trend of the traffic information transition is the technological availability of onboard electronic devices. Various experimental programs, for some Europe-funded, associate the public sector, the car industry, telecommunication companies, and private service providers. Among the oldest of these, Prometheus (Programme for European Traffic with Highest Efficiency and Unprecedented Safety), launched in 1986, labelled among the EUREKA projects, gathered public research institutions, manufacturers, European automobile manufacturers like the French PSA and Renault. By the late 1990s, the Internet Revolution allows the rise of numerous private stakeholders, which provide drivers traffic information originally based on road authorities' data, and gradually complemented by data retrieved from the users themselves. Traffic information shifts increasingly toward the private sector, with an individualized service relying on users data, but also for a part on public information, mostly to check the validity of signaled events (road closures, demonstrations, roadworks, accidents). Traffic management systems, until then solely visible to the driver through the VMS, see their traffic sensors information broadcasted on the Internet. The 1996 launch of the Sytadin portal (Synoptique du Trafic de l'Ile de France) was the outcome of the Paris region public traffic information policy. Sytadin broadcasts the traffic data and events from the State network, the City of Paris network (major arterials and ringway), and motorway concession companies within the region. The CORALY system (Coordination et régulation du trafic sur les voies rapides de l'agglomération lyonnaise) in Lyon, followed up on Paris with a slight delay, as the centralized computer system was only set up in 1998, and its Internet availability in 2002 [104].

It is somewhat of a paradox that as the road authorities' traffic data collection systems reached their maturity (comprehensive coverage of major expressways and arterials, extensive broadcasting of the data through the Internet, phones, VMS), the infrastructure they rely on, traffic sensors, begin to cede ground. Some politicians complained about it: "the dynamic map of the network shows [...] grey sections corresponding to unavailable traffic data. There are plenty of such zones, often at strategic locations of the network, thus questioning the interest of the system" ([105]). Moreover, public portals are restrained to the boundaries of the authorities behind them, and the roads they administer. For the Paris region, the traffic data collection systems of the Départements bordering Paris are not available on Sytadin. At the same time, private companies have based their web portals on the public ones (with the dynamic traffic map and the color-coded traffic conditions), but thanks to their user base they are able to provide a far more extensive spatial coverage of the road network. This includes roads that do not have sensors, roads whose sensors are out of order, and even local streets. The situation in Lyon seems less problematic, as the various local governments show more union around these issues and congestion is mostly limited to a few major arterials and expressways, plus the downtown Lyon arterials.

Additionally, current drivers' information policies are now part of broader multimodal policies, in line with the policies implemented in Paris and Lyon since the 1970s. Indeed, VMS messages adapt a "common language" with other transportation modes, by delivering "journey travel-times" to the traffic (since 1994 in Paris, for example). Nevertheless, a fundamental difference can be drawn between Paris and Lyon's policies, regarding the multimodal approach within the transport authorities' transport information portals. In Lyon, all major modes (transit, car, walking, bike) available for a journey are centralized within the same portal, Onlymoov, which integrates traffic data from the CORALY system. In Paris, the roads authorities' portal Sytadin is independent of the multimodal portals, like the region's portal ViaNavigo. Sytadin remains focused on the car, whereas ViaNavigo, launched by the Syndicat des Transports d'Ile de France in 2011, completely excludes motorists from its route planner [2]. Political orientations and authorities' range of action seem to outweigh the transport user interest in the display of traffic conditions. Moreover, ViaNavigo is a website of the Regional authorities, who do not have as of 2017 authority on roads, whose responsability is split between the State, the Départements, the City of Paris and the various municipalities. The Lyon portal evolves in a different context: Onlymoov is one of the outcomes of the Optimod project, which was designed to overcome usual administrative boundaries.

Drivers' information has throughout the 1970s to the 1990s transitioned from static information systems to a dynamic centralized management of traffic flow, still governed by roads authorities but with an increase of private interests. These public systems then get challenged by crowdsourced systems as the drivers themselves become sensors through the growing fleets of onboard units. These crowdsourced systems however remain rather fragmented as each company has its own user base. Routing instructions provided by these private stakeholders do not necessarily follow the public traffic management policies.

3.4 Conclusion

The study's long-term perspective shows a broad trend towards a deeper relationship between drivers and urban roads authorities. Drivers' information management triggers the creation of dedicated technical system and public services. Driver's information infrastructures are essential to analyze the evolutions of traffic management policies: roads authorities of Lyon and Paris had to adapt to a lot of changes in traffic flows, technical innovations and the necessity of coordinated traffic policies. From giving the right direction to occasional drivers to fighting congestion, the aims of signposting schemes have changed. They were integrated in global traffic management policies, both in Lyon and Paris. Since 1950s, drivers are considered as a part of a traffic flow, but also as a source of data. This is the main concern for the innovative dynamic information systems and centralized traffic management schemes developed by public roads authorities in the two cities.

The history of driver's information infrastructures can also be a history of adaptations and failures. From the 1930s to the 1970s, the technical systems have changed with innovations and changing policies, but the administrative framework of roads authorities remained the same. It is one of the major cause of the overtaking of public driver's information systems by private ones, since the driver himself becomes a data producer starting in the 1990s. In 2017, the link between drivers and road authorities is now shared between a lot of public and private actors: it increases the differences of drivers' information systems between cities, as shown by the example of Paris and Lyon.

[2] Since late 2017, ViaNavigo includes an experimental car-sharing option

Figure 3.1 – Signpost on Avenue des Champs Elysées. "Avenue prohibited to public harnessed carriages with more than two horses, and to suspended or not suspended transport carriages" "Avenue interdite aux voitures publiques attelées de plus de deux chevaux et aux voitures de roulage et de transport suspendues ou non suspendues.". Charles Marville (photograph), circa 1870. Charles Marville, Bibliothèque Historique de la Ville de Paris, Roger-Viollet.

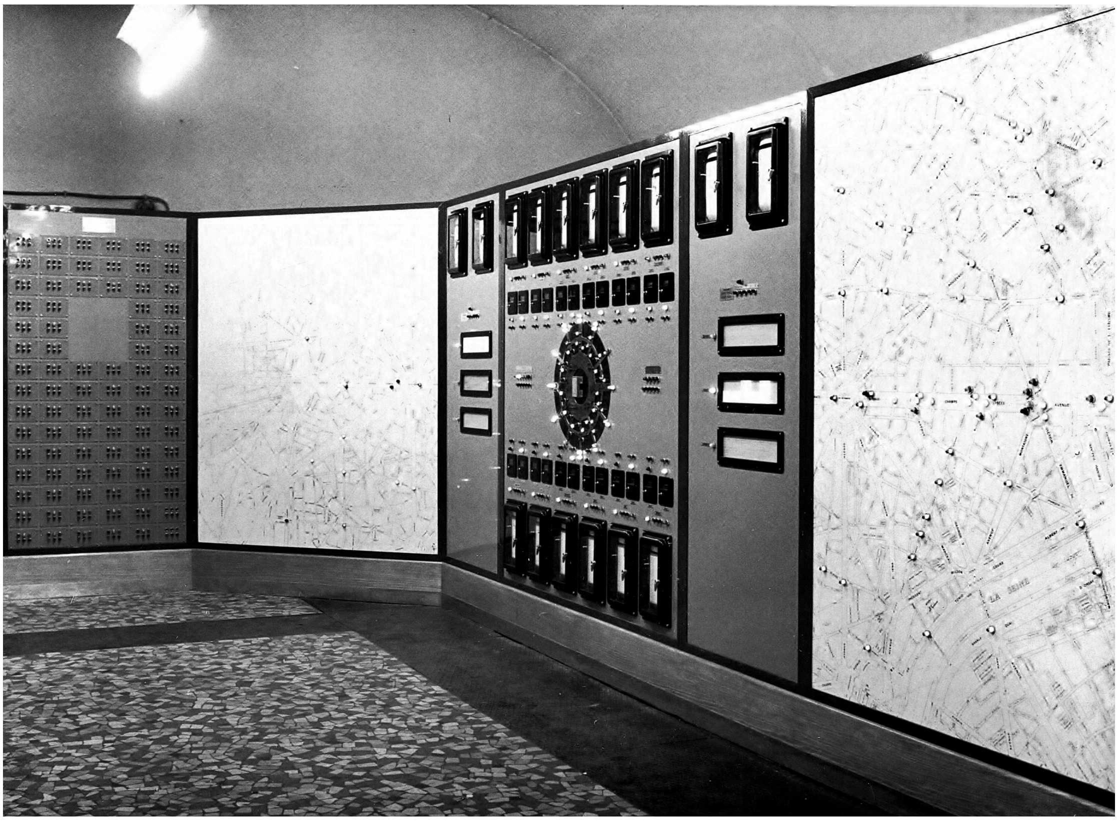

Figure 3.2 – Poste Maillot control room, circa 1956. Picture from the Laboratoire des Équipements de la Rue (Paris Streets Assets Laboratory) archives, reproduced by the authors with the kind authorization of the late lamented Pierre Leroy, in charge of the Traffic and Signals Division of the Laboratoire from 2000 to 2017.

Figure 3.3 – Arrow signal bearing "Maine only" (referring to the Avenue du Maine, in Paris), at the signalized junction between Maine, Montparnasse and Vaugirard arterials. Picture circa 1950, from the Laboratoire des Équipements de la Rue (Paris Streets Assets Laboratory) archives.

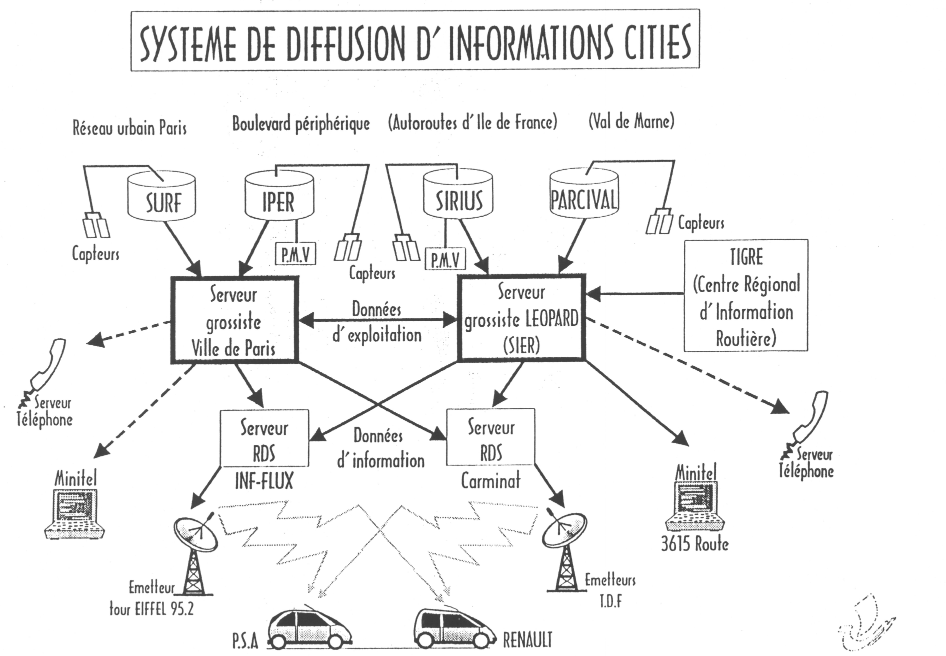

Figure 3.4 – Diagram of the planned CITIES traffic information broadcasting system. Document from the Direction de la Voirie et des Déplacements, Ville de Paris, 1995.

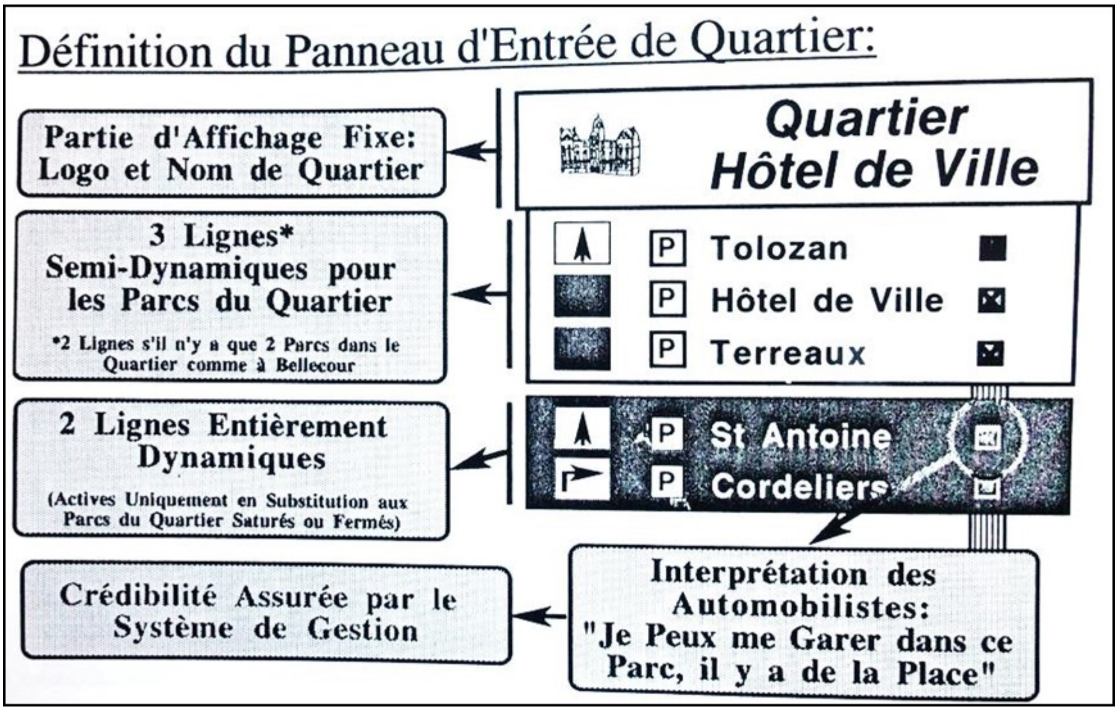

Figure 3.5 – Proposed sign for an Area Entrance Sign, for the dynamic signposting scheme of Lyon's parking lots, in 1993 (AML1781W63).

Conclusion of the First Part

Part I addressed the following issues:

1. How has traffic data answered the operational needs of the road authorities, and allowed the inception of both traffic engineering and of the Traffic Management Centers most urban road network are headed by? Should "new" traffic data really be opposed to "legacy" traffic data?
2. What have the successive technical advances of the traffic data collection and traffic information broadcasting, from the 1920s to the 2010s, meant for the Traffic Management Centers' relationship for the drivers? How is that relationship challenged by today's widespread use and collection of crowdsourced traffic data?

Chapter 2 answered the first issue: How has traffic data answered the operational needs of the road authorities, and allowed the inception of both traffic engineering and of the Traffic Management Structures most urban road network are headed by? Should "new" traffic data really be opposed to "legacy" traffic data?

Road maintenance and improvement have from the start been the key motivations behind traffic data collection. As a link was drawn by road authorities between road condition and the volume of traffic, traffic count became the first of traffic data to be methodically collected.

Rising traffic demand yielded an additional question: how many cars could a highway cope with? Congestion became an issue, and capacity gradually a variable to estimate it and quantify the needed improvements on the infrastructure.

Road and traffic research is institutionalized, in the line of the Eno Foundation, and multiple experiments are carried out to observe and quantify traffic. Works by Johnson, followed by Adams and Greenshields, yield first definitions of vehicle gap and headways, velocity, density, volume, although the terminology of the time is not necessarily the same than today's. In an effort to quantify and predict congestion, first investigations are carried out on the relationship between velocity and density, velocity and volume. The first theoretical background is given by the theory of probability.

Two means of observing traffic were experimented: ground-based spot observations and aerial observation. Both of them yielded their set of definitions, and already raised the dilemma posed by these two methods. The road authority wants to have thorough knowledge both in space and time of the traffic on its network.

Spot surveys are "cheap" but only provide data at a specific location over periods of time. Aerial surveys provide much more extensive spatial information, but at great cost and only at a specific time.

These works aimed at understanding and quantifying traffic for road maintenance and planning reasons. Theory could help plan future behaviors without necessarily requiring extensive measurement campaigns that were tedious and expensive.

During the two decades that followed the war, from the 1940s to the 1960s, much of today's traffic variables were precisely defined, based on the experience gathered from the early twentieth century and the refinement of observational techniques.

All the traffic engineering manuals shared the common goal of offering a comprehensive review of existing principles and practices regarding traffic engineering. They concentrate on operational variables, for which we can already perceive two overlapping categories. The first one includes variables relative to the traffic stream or traffic flow, with the speed, the volume and the capacity. The second one covers the network performance or efficiency, with the travel-time (and its associated journey speed or over-all speed) and the volume considered within origin-destination studies.

Beyond the definitions they provide, these manuals also offer insight on the methodologies available at the time, but also on the motivations standing behind this whole branch of engineering. These range from maintenance to the issues of safety, congestion which is seen as something meant to be overcome, to more explicitly the performance of the network, through its efficiency.

Sign of their usefulness, the stability of these publications is worth noting, as most of these books have been repeatedly updated until today.

Traffic flow variables are: flow, concentration, speed. These are brought up as the analogy between traffic flow and the fluid theory, already felt in the 1930s, is formalized. The definition of the variables remains closely associated to how they are measured, schematically either from a spot on the road (Eulerian observer) or by a moving observer (Lagrangian observer).

They are defined over a rather imprecise scale by Wardrop, and then by Lighthill and Whitham: Edie proposed a generalization of the definitions over a random space-time area, which somehow solved the problem at least analytically. Nonetheless, the minimum time duration of spot observations remains in question.

The average issue (either space or time) is closely linked to method of data collection (spot observation or from the air), as identified by the authors. Time-mean speed is the easiest to collect at a point on the road, whereas the meaningful speed for drivers is the space-mean speed, which is the reciprocal of journey time.

The relationship between flow, concentration and speed becomes known as the fundamental diagram, and is meant to summarize the resulting interaction between demand (drivers) and the supply (infrastructure), which is traffic.

The operational needs calling for global indicators, such as vehicle kilometers traveled and travel-times, were already identified in the early days.

A compromise with the available technology had to be found.

This is true for vehicle kilometers traveled estimates. It relies on traffic counts, which are "easier" to collect than any other traffic data. It also depends on the average length of trips, which is much harder to catch.

Travel-time is a step further in complexity: various and more or less complex sampling method were set up, but that would only give partial results at great cost. Studies of travel-time however raised remarks on their distributions that are still valid today.

Paris case shows that the road network was quickly thought like a system to be managed, and not only an urban space. Traffic data answered the need for quantification of "what was on the streets", and played a key role in defining policies to deal with the traffic. These policies were at first oriented toward road building, and then gradually switched to an "information" infrastructure, paralleling the main arterials of the road network, and used by the traffic lights management system. A new network, parallel to the road network, was thus created and gradually expanded, to monitor it real-time, thanks to thousands of traffic loops. The sensors not only served the traffic lights actuation algorithms: they were installed for statistical means. They yielded data allowing real-time computation of vehicle kilometers traveled and average speed estimate indicators that have since then played a key role in assessing traffic-related and street-related policies in Paris.

Nonetheless, the complexity and large spatial coverage of this network of sensors in some way causes its gradual dismal, under various factors. These include a rising number of stakeholders working on the streets (telecom, energy, transport companies), aging assets in need of renewal, and increased safety procedures for the roadworks required to restore sensors.

Chapter 3 addressed the second of the aforementioned issues: What have the successive technical advances of the traffic data collection and traffic information broadcasting, from the 1920s to the 2010s, meant for the Traffic Management Centers' relationship for the drivers? How is that relationship challenged by today's widespread use and collection of crowdsourced traffic data?

Paris and Lyon cases illustrate the gradual evolution of the relationship between the driver and the road authority, from an exclusive link to a shared one, and how it shaped the road authorities.

From the 1920s to the 1950s-1960s, the road authority both manages the infrastructure and the traffic as one same homogeneous set. The driver is rather "free" and his relationship with the authority quite loose, limited to the road and the signs. The said relationship can also be shared with private companies who provide some signs on behalf of the authorities (Citroën, Michelin).

Around 1970, the driver-authority relationship changes radically with the overall expansion of real-time traffic data collection infrastructure, the result of the industrialization of existing traffic sensing processes. The road authority gains a real "traffic management" function. Traffic Management Centers are born, providing a real-time monitoring of the network, and interaction with it through the traffic signals. An exclusive relationship links the traffic management entity and the driver. The authority sends information to a flow (and not individually) and the driver (as an individual) generates information through the road infrastructure, thanks to the sensors, that only send "flow" variables to the authority.

Around the mid 1990s, the centralized systems are mature and traffic information broadcasting circuits are in place. The exclusivity of the link between the driver and the authority yields ground, as public infrastructure begins to decline, and more importantly, as the driver (or his vehicle) himself generates data individually, through an individualized link between him and private service providers.

Part I showed that traffic data answered from the start key operational concerns of the road authorities, and subsequently of the Traffic Management Centers. Technical advances have allowed a gradually more comprehensive traffic data collection based on fixed sensors, which allowed to get a real-time global view of the network from one centralized location. Beyond the curiosity that initiated traffic research, traffic theory has come to back the operational issues encountered by the road authorities and TMCs.

The rise of crowdsourced probe traffic data seriously challenges the centralized structure of the traffic data collection system, and beyond this of the Traffic Management Centers' monopoly on traffic data, and which mostly rely on these systems.

The upcoming Part II will now focus on the operational use of some of these "new" traffic datasets by the Traffic Management Centers.

Part II

“New” traffic data: expanded ways to assess traffic

Introduction to the Second Part

Part I showed the role played by traffic data to answer the operational needs of road authorities and associated Traffic Management Centers.

The 1990s constitute a turning point in the knowledge of traffic and the collection of traffic data. Until then, traffic data was collected on behalf of and for the road authority. It was done either through road-based sensors or dedicated vehicle fleet, and traffic theory built upon both Lagrangian and Eulerian measurements. Traffic variables have been defined for both of these methods, but most traffic databases consist of Eulerian measurements.

Starting in the 1990s, the vehicles, and then the drivers themselves, have been sensing their own journeys, mainly because the technology became available and affordable: radio beacons, GPS receivers, then smartphones[3] embedding various functions. These devices generate what can be called "new" traffic data.

In 2017, this has major consequences:

- Lagrangian traffic data can be collected at an unprecedented and growing scale, gradually overwhelming the existing fixed sensors infrastructure of the TMC;
- Private companies have a hand on the data produced by the onboard terminals, which are not designed or controlled by the road authority. This implies that the exclusive relationship between the traffic and the road authority, which was the only one able to comprehensively see the traffic, is bypassed by other relationships linking service providers and drivers;
- Traffic is not only seen as a flow, as seen through the traffic sensors, but drivers themselves generate individual data that is seemingly not directly caught by the authority;
- These technologies give comprehensive travel-time and speed datasets, which have been sought for since the early days, as shown in Part I, but which could not be collected at this scale with predating technologies.

Part II addresses the two following issues:

1. What data can the TMC "catch" outside of its legacy sensors infrastructure?
2. What are the operational traffic indicators these "new" traffic data provide? What operational purposes can they serve for the Traffic Management Center?

This part answers these two points based on the experiments lead by the author during the 2014–2017 period while he was an engineer at the PCE Lutèce, the TMC of the City of Paris.

Beyond the data produced by its extensive legacy sensors infrastructure, the PCE Lutèce was able to acquire two kinds of "new" traffic data. Both of these technologies are part of the broader *Floating Car Data* designation, which refers to data generated by individual vehicles during their journey. This data generally contains timestamped anonymized identifier, position, speed, or travel-time values. It is either directly generated onboard the vehicle, or caught by a roadside unit:

Bluetooth travel-times, obtained thanks to d.edicated sensors implemented on the roadside

[3] According to the Merriam-Webster dictionary, the word first appeared in 1997.

and detecting MAC addresses of Bluetooth-enabled equipments. Bluetooth probe data relies on roadside units that makes timestamped detections of the MAC addresses of the equipments (among which onboard equipments) traveling in their vicinity. Pairing MAC records and associated timestamps from two beacons yields a travel-time per equipment.

GPS-based Floating Car Data speed, tendered through a private service provider which had archived real-time speed data retrieved from a fleet of GPS terminals. GPS-based probe vehicle data relies on the GPS receiver aboard the vehicle that elaborates data during the journey, and transmits the data to a server over the cellular data network.

From the start, the primary, underlying goal of the author's work on these two datasets was to assess the traffic conditions consequences of major political projects (infrastructure closure, speed limit reduction) over the City of Paris road network. Therefore he used off-line datasets, real-time use being beyond the cope of the present work.

With rising concerns on loop detectors failures, and many traffic-impeding projects to assess, the PCE Lutèce was eager to test new technologies that would provide richer information than its historical infrastructure could deliver. The greatest need expressed by many was the collection of travel-time values. The PCE Lutèce seeking systems that would provide more reliable travel-times than through the historical *BRP* algorithms based on the loops data, whose results were becoming increasingly dubious as sensors were failing.

Chapters 4 and 5 focus on the travel-time indicator, as collected through Bluetooth travel-time technology to assess two major, disruptive traffic-impeding decisions. The first, in 2015, is the closure of an underpass under one of Paris major intersections, the Place de l'Etoile. The second, in 2016, is the closure of a major cross-city expressway. In both cases, the purpose was to assess Bluetooth travel-time usefulness in keeping track of travel-times before and after the disruptive measure.

Chapter 6 focuses on GPS-based FCD speed data, and the difficulties met in using the data. It shows that, even though not relying on authority's ground equipments, this "new" dataset is not, as already shown by Bluetooth, straightforward or "plug-and-play".

Chapter 7 treats a major speed-related issue: assessing the lowering of speed limit in Paris, with two cases. The first case is the lowering from 80 to 70 km.h^{-1} of the speed limit on the ringway, and the second is the establishment of 30 km.h^{-1} zones. GPS-based FCD allows the collection of instantaneous speeds of vehicles throughout the network.

The data analysis relies on the empirical distribution of traffic-related variables (travel-times, speeds, etc.), and sometimes on the comparison of distributions between two periods. These variables are often strongly time-dependent, as traffic is.

In standard statistics, distribution fitting or comparison between distributions relies on statistical tests, like the well-known χ^2 or Kolmogorov-Smirnov test. The use of statistical tests has been subject to much debate since the beginning of traffic engineering. This debate was essentially fueled by "the Poisson traffic assumption" initiated by Kinzer and Adams in the 1930s. In 1952, Greenshields and Weida published the first manual dedicated to applying statistical techniques to traffic data [37]: for goodness of fit tests (to Poisson...), it relied on the χ^2, the "usual method of making a test of goodness of fit" ([37, p. 177]). Nonetheless, during about the same period, in 1955, Gerlough [106], writing on the *Use of Poisson Distribution in Highway Traffic*, tests the adequation to the Poisson distribution of various observations through the χ^2. He nonetheless warns the reader that "an acceptable χ^2 test is less conclusive than one which fails. The rigorous interpretation of an acceptable test should be, 'There is no evidence to indicate non-randomness of the data'" ([106, p. 16]).

Throughout the traffic literature, there is debate on the "strength" of the various tests, which seem to depend on the context, the data analyzed, and the authors' own philosophy. For instance, Breiman et al. in 1977 [107], in order to test goodness of fit of headways on a freeway to an exponential distribution, "after some preliminary investigation, [...] decided that the Kolmogorov-Smirnov test was more powerful in this situation than the χ^2-test" ([107, p. 223]).

In the end, one may ask: "isn't the test chosen so that it yields results compatible with the authors' assumptions?"

In 1995, Newell, in his *Theory of Highway Traffic Flow 1945–1965* manual, stated, still on the Poisson distribution for traffic: "it is rather difficult to devise a meaningful statistical test for the hypothesis that a traffic stream is Poisson distributed. Cars have finite size and interact strongly at close headways. The Poisson process is certainly not an exact representation of traffic, and one can devise statistical tests (sensitive to short headways) which would almost always lead one to reject the hypothesis that the traffic is a Poisson process. The conventional theory of statistical testing is not ideally suited to the rather poorly defined question: is a hypothesis (known to be false) approximately correct? It would be possible to devise some suitable tests, but the logic would become rather involved" ([9, p. 38]). Newell's last question could well be asked for any traffic-related data.

The Poisson case illustrates the doubts that have surrounded the use of conventional statistical processes in traffic engineering. Moreover, the complexity involved in developing "suitable tests" or interpreting complex statistical tests goes beyond the scope of the present work. Therefore, the author decided to rely on graphical and descriptive analysis for most of his work on the distributions. He only seldom used statistical testing: only for very specific purposes that will be highlighted when they are used.

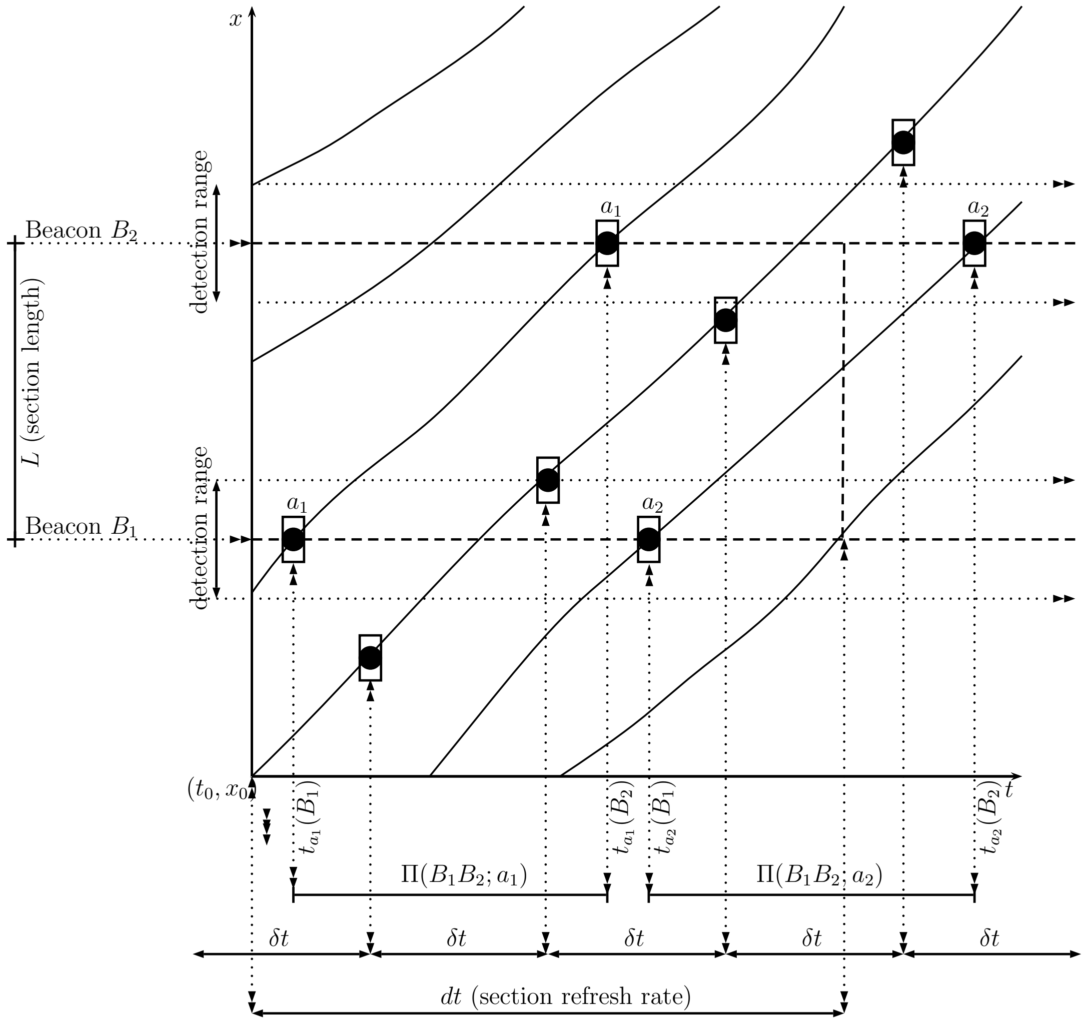

Figure 3.6 – The two "new traffic datasets" investigated by the author, drawn upon an $x - t$ diagram.

Figure 3.7 – Diagram of the methodology of the author's experiments presented in Part II

Chapter 4

Place de l'Etoile: First encounter with Bluetooth beacons

4.1 Closing a tunnel under one of Paris' major traffic hubs

Located on a hilltop, the Place de l'Etoile[1] is one of Paris most symbolic squares. It is a circular plaza at the center of which sits the Arc de Triomphe, and from which twelve avenues radiate out, including the famous Champs Elysées and Grande Armée avenues.

For West Paris, the place de l'Etoile is the main intersection between important radial routes, either reaching the city's limit and the ringway (Foch and Grande Armée avenues), the city's (Champs Elysées and Friedland avenues), or acting as an intermediate urban ringway locally known as the "Fermiers Généraux", followed by subway lines M2 and M6, halfway between the city's core ringway (along the former fortification wall, known as the "Grands Boulevards") and outer ringway (the "Boulevards des Maréchaux" and their expressway counterpart, the "Boulevard Périphérique").

Traffic-wise, the square was turned into a roundabout in the early XXth century, with a right-hand traffic priority regime that is still in place today: vehicles traveling on the circle must give way to cars entering the circle on their right. Tram lines that used to go through the plaza were shut down in the late 1920s and early 1930s.

Since the 1960s, a 400 m long tunnel underneath the northern side of plaza has allowed free flow movement for cars traveling from the Champs-Elysées to the Grande Armée (from East to West). Its southern counterpart, meant to provide grade-separation to traffic flowing the opposite way, was planned but never built.

Throughout the years, due to its low clearance (2.40 m), which only allows standard passenger cars through, numerous vehicles have struck the tunnel's entrance, despite the warning signs put in place. It gradually became a subject of concern, combined with the dangerousness of its in and and out ramps for pedestrians and cyclists wanting to cross them, the tunnel itself being prohibited to non-motorized traffic[2] [109]. Moreover, the tunnel needed heavy refurbishment for it to comply with the latest tunnel safety regulations. Facing the cost of such operation, involving several million euros, the City of Paris decided to investigate the tunnel's closure.

The Place de l'Etoile being a very strategic intersection, and given the traffic volumes at stake, it was decided to temporarily close the tunnel in order to have a real-case evaluation of

[1]The plaza is officially named "Place Charles de Gaulle" since the General's death in 1970, nevertheless most people continue to call it by its historical name "Place de l'Etoile".

[2]A blogger even reports some of the accidents on a dedicated website [108].

the consequences of its closure on traffic conditions. It is a traffic circle with right-hand priority to entering traffic, and all inbound avenues are controlled by traffic lights upstream from the circle, which itself is free of any light.

The tunnel closed on March 16th, 2015.

The main concern of the City of Paris and of the Préfecture de Police was whether, once the tunnel would be closed, whether the plaza would be turned into a complete gridlock or not. For people with a long empirical and operational knowledge of how the plaza worked, especialy when the tunnel was blocked by an accident, the critical aspect of the closure was how cars coming from Grande Armée (the West) and aiming at Friedland (the North-East), would interfere with cars coming the Champs-Elysées, the latter having priority over the former.

Operationally, this translated into addressing the two following questions:

- How much time is needed to cross the traffic circle coming from the Champs Elysées to Grande Armée?
- How much time is needed to cross the traffic circle coming from Grande Armée and turning onto Friedland?

The author, by its position at the PCE Lutèce, had to come up with a plan.

The two usual, legacy, “traditional” methods were thought of.

The first legacy method involves the SURF system sensors infrastructure, and the volume VKT and BRP average speed V_{BRP} indicators derived from them. Nonetheless, this method was not suitable for the aforementionned operational questioning, as no traffic sensors have been implemented on the plaza itself (given the width of the circle's roadway, implementing loops on it made no real sense and would have technically been very complex). The legacy indicators could therefore only be used to assess the traffic on the corridors themselves, but not the traffic movements on the plaza. Moreover occupancy and flow data yields very limited information on origin-destination patterns and travel-times. Some sensors were also out of order, compromising even more a study fully based on loop data.

The second legacy method would involve a manned license-check study. Nonetheless, the width of the roads (four to five lanes of traffic for some avenues) and the levels of traffic involved made it a highly unsatisfactory option.

The legacy methods failing to answer the need, and knowledge of Bluetooth beacons travel-times experimented elsewhere in France led the author, along with his colleagues, to propose experimenting the technology. This would allow to give a quantitative answer to the “how much time?” questioning.

4.2 Diagnosis of the traffic conditions on the place de l'Etoile through the legacy sensor-based method

The Place de l'Etoile faces traffic levels on its radiating avenues close to some of the express-ways of the Paris region network.

Although the legacy sensor-based method was not appropriate to answer the aforementioned operational travel-time questions regarding the intersection proper, they are nonetheless useful to assess the traffic conditions on the major arterials radiating in and out of the intersection.

Both traffic counts and the two indicators derived from traffic loops data, namely the VKT_{norm} volume and the V_{BRP} average speed indicators, are used on the two main arterials connected to the roundabout: the Grande Armée and the Champs-Elysées avenues.

Of all the plaza's radials, the East-West axis (the Champs Elysées and Grande Armée) is the most heavily trafficked. The Grande Armée is in fact one of the busiest arterials in Paris, carrying an average 40,000 veh/day Average Daily Traffic (ADT) each way on business days (the 50,000 veh/day recorded on the outbound traffic lanes is overestimated, as it was found the traffic loops over-counted vehicles). The Champs-Elysées hold similar traffic levels, with over 35,000 veh/day each way. For the westbound traffic, out of the daily 38,000 vehicles, 20,600 were recorded in the tunnel and 17,700 on the surface (not all of the latter vehicles are bound for Grande Armée).

Busy arterials see daily traffic averages between 10,000 and 20,000 veh/day inbound and outbound the plaza : Foch (15,200 inbound, outbound unknown due to a failing sensor), Wagram (inbound unknown due to a failing sensor, 21,500 outbound), Mac-Mahon (11,500 inbound), Friedland (12,700 inbound and outbound), Marceau (17,000 outbound).

Complementary to in-situ traffic counts analysis, two indicators, computed on a given arterial I out of occupancy $O_{i \in I}$ and flow $Q_{i \in I}$ measured by the traffic loops, are used when analyzing traffic on Paris arterials:

The Normalized Vehicle Kilometers Traveled (VKT_{norm}), in vehicle kilometers per kilometer, is weighted average of the available flow measures for the corridor over which it is computed The value it yields is, if the considered corridor is modeled into a 1 km long section, the average flow a theoretical sensor would measure on that model.

The BRP average speed V_{BRP}, in km.h^{-1}, is an analytical derivation of speed from available occupancy and flow measures.

Champs-Elysées and Grande Armée avenues are, given their ADT, the two major radials. The two aforementioned indicators were computed for each of them from data aggregated per 15-min intervals, t_{15min}, over the business days from February 1st to March 15th, 2015.

On the Champs Elysées, the VKT_{norm} for Eastbound traffic is higher than Westbound (Figure 4.4). The BRP average speed for Eastbound is lower than Westbound, especially during the evening peak, whereas the Westbound speed follows a constant trend throughout the day (Figure 4.5). In fact, until Summer 2016, the Eastbound Champs corridor directly led onto the West-East free-flowing Georges Pompidou expressway, with a grade-separated interchange under the Place de la Concorde, hence providing a fast outlet to traffic in this direction. When looking at general sensors availability over this corridor, it appears that only 50 % of them were in working order, which influences the resulting indicators. The VKT relies on two out of four traffic count stations (two being out of order), and the analytical BRP speed is only computed on half the corridor's length. Available data however yields a crucial information: the West-East direction seems to be congested between 16:00 and 19:00, the worst being around 17:00 (lowest BRP value of the period), and carries more traffic than the Westbound direction.

According to traffic sensors data, Westbound traffic roughly splits in two halves upon arrival at the Place de l'Etoile: one half bound for Grande Armée through the tunnel, one half bound for other destinations and thus forced to use the roundabout. The ADT (17,700 veh/day on the surface and 20,600 veh/day through the tunnel, which sums up to 37,700 veh/day) measured by the sensors on the Champs Elysées are blatantly in contradiction with the VKT, which is on average equal to 1,500 veh.km/km for 12 hours, and between 200 and 1,000 veh.km/km for the rest. Sensor 0214Q01 turned up to be faulty: over the thirty business days from February 1st to March 15th, there are 14,400 t_{03mn} aggregation intervals. When looking at the sensors data, the tunnel sensor 0214Q00 returned 14,307 valid values, whereas the surface sensor only returned 6,072 valid values. The maintainer had to intervene several times during the observation period to reset the traffic count station faulty hardware. The over-counting issue was confirmed through a manual vehicle count.

Sensor 0214Q01 daily failure rate over the reference period, is plotted on Figure 4.2. It shows that the sensor was completely out of order for half the time, with only 9 days (out of 40) with a failure rate of less than 10 %. Time analysis by t_{03min} intervals shows a relatively uniform average rate of failure, with nevertheless more failures at night (over 60 %) than during the day (around 40 %). In fact, at night, as shown by Figure 4.15, traffic is lighter: when a loop doesn't see any traffic for more than a given time, an alarm is automatically raised onto the central system, and it must be manually overridden by a control room operator past a certain duration. An alarm might also be triggered by faulty hardware; as a traffic loop is not considered as a critical component of a traffic light junction, several days may pass until a crew is sent on site to diagnose and, if it can be done, solve the problem. During the alarm period, no data coming from the sensor is stored onto the SURF system's database.

Of interest is the "fundamental diagram" of each corridor, plotting each instant $t_{15min}(x, y)$, with x the corresponding VKT_{norm} value and y the corresponding V_{BRP} speed value, as shown by Figure 4.6). The resulting scatter shows that the East-West Champs operates at a lower VKT range (200 to 1,600 veh.km/km) than the West-East Champs (200 to 2,100 veh.km/km). Relating the plot to previous VKT_{norm} (Figure 4.4) and V_{BRP} (Figure 4.5) time series, dispersed VKT_{norm} values at roughly constant speed reflects night-time operation of both routes, whereas for day-time operation, points agglomerate around two distinct points: one for each route. Congestion is hinted for the West-East route, as there is a downward tendency in BRP speed for high values of VKT_{norm} (above 1,600 veh.km/km).

Grande Armée, as a major arterial linking the *Fermiers Généraux* urban ringway and *Porte Maillot*, a major motorway interchange with the *Boulevard Périphérique* and the N13-A14 expressway, clearly shows the conventional city-bound traffic movement in the morning, the opposite suburb-bound movement in the evening, the trend inversion occurring around noon. Nevertheless, at the time, Grande Armée suffered from an even higher rate of faulty traffic stations than the Champs: 20 % for West-East traffic, and 45 % for West-East traffic. Most occupancy stations were out of order, and only one traffic count station was working per direction (instead of the nominal two per direction). Moreover, the high VKT_{norm} value (Figure 4.7) for night traffic on the Westbound direction looks suspicious, but given the road width (four to five lanes), it was difficult to evaluate the overcounting rate of the sole traffic count station still in operation for that direction. BRP speed is off-track with such low equipment availability, with suspicious variations (Figure 4.8). The fundamental diagram is given for the record (Figure 4.9), and shows that both ways basically operate around the same range of values of VKT_{norm} and V_{BRP} speed during the day.

This shows how much VKT_{norm} volume and V_{BRP} speed indicators heavily rely on the good state of the traffic stations, something which is hard to guarantee in an urban environment, as aging equipments and ongoing roadworks quickly translate into scarce data.

From the sensor-based method, the Place de l'Etoile stands as a major interchange of Paris road network. The Grande Armée and Champs-Elysées axis constitutes the major route across the plaza both for Eastbound and Westbound traffic, and underlines the key role of the tunnel in allowing free-flowing Westbound movement from the Champs to the Grande Armée.

Nonetheless, the low availability of traffic stations, especially at key locations, and the suspicious reliability of a part of the working ones, impede the reliability of the indicators. They do yield traffic trends (the pattern of commutes, city-bound in the morning and suburb-bound in the afternoon), but the values must be taken with great care.

Therefore, assessing the tunnel's closure had to rely on alternative existing technologies to measure travel-times or speeds in an urban environment.

Floating Car Data, derived from GPS data was one, but the study of travel-times through the tunnel made it difficult to implement. Consider a vehicle traveling from Champs Elysée to Grande Armée and equipped with a GPS receiver. Inside the tunnel, the GPS receiver wouldn't be able to send any data (too much concrete!), so his route (either through the surface or the tunnel) would have to be inferred based on his travel-time, as known positions of his vehicle would be before and after the tunnel.

Bluetooth technology came up through a contact the author had at the Poste Central d'Exploitation Berlier, the Traffic Management Center in charge of the Boulevard Périphérique. In fact Bluetooth technology had already been tested for a few years on various interurban corridors in France, including a section of expressway in Paris vicinity.

The author then met with the French company Néavia, which had designed and was selling the Bluetooth beacons solution, known as "Bluevia".

Funding was made available to buy four of these beacons. As the devices would have to be installed on streetlight poles, the company in charge of the maintenance of streetlights assets in Paris, EVESA, was closely associated to the experiment.

Néavia provided the beacons and the installation guidelines, and the personnel required to configure the beacons on site. EVESA provided the required technical and personal means for the installation. The author coordinated the operation.

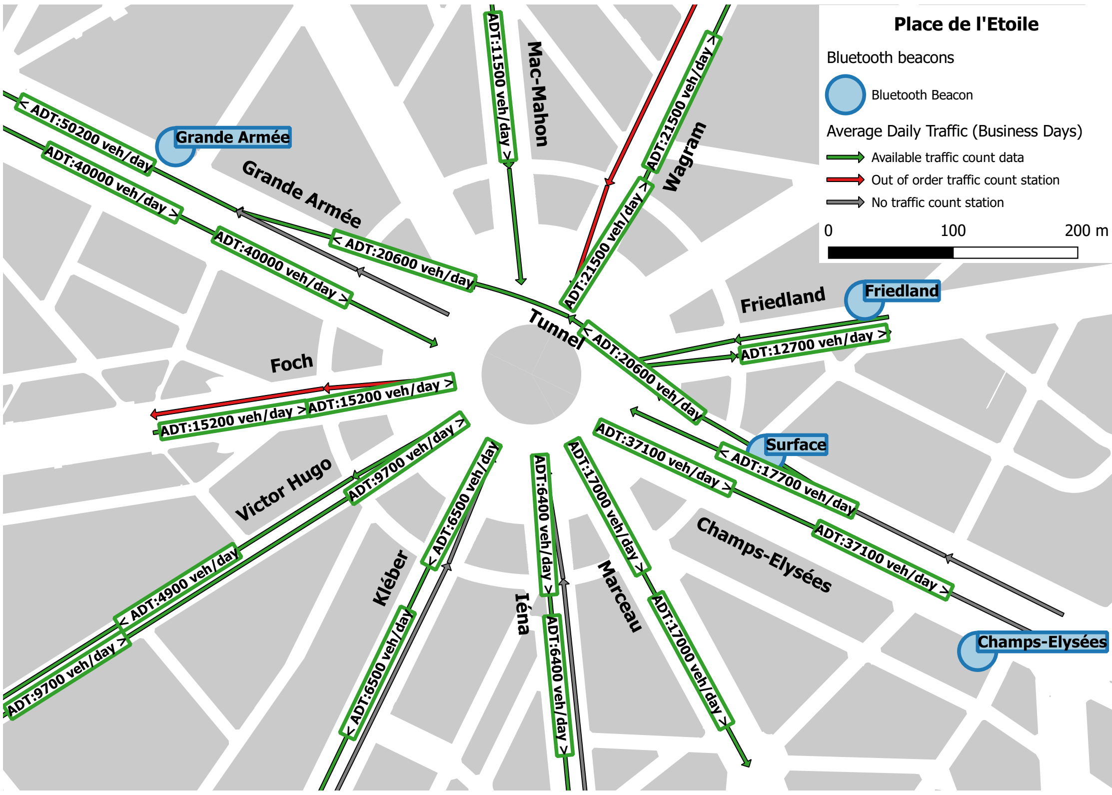

Figure 4.1 – Place de l'Etoile map. Average Daily Traffic volume, over business days from February 15th, 2015 to March 31st, 2015. Approximate locations of the Bluetooth sensors.

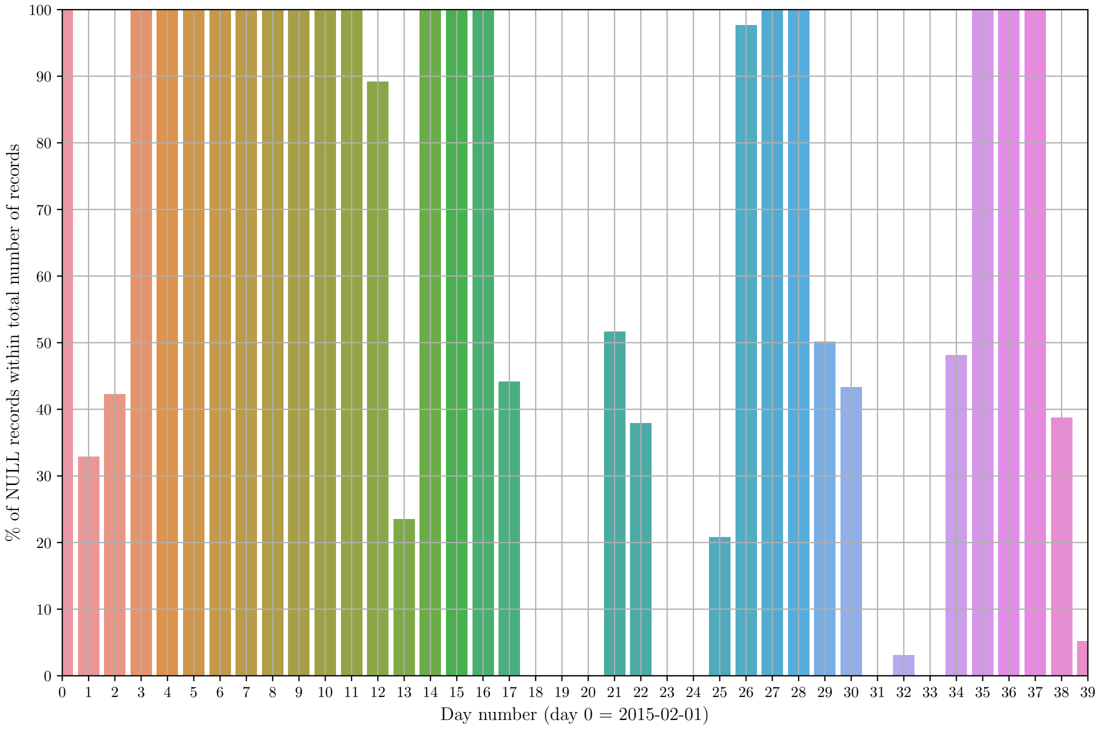

Figure 4.2 – Traffic count station 0214Q01. Daily data Availability over reference period (including weekends).

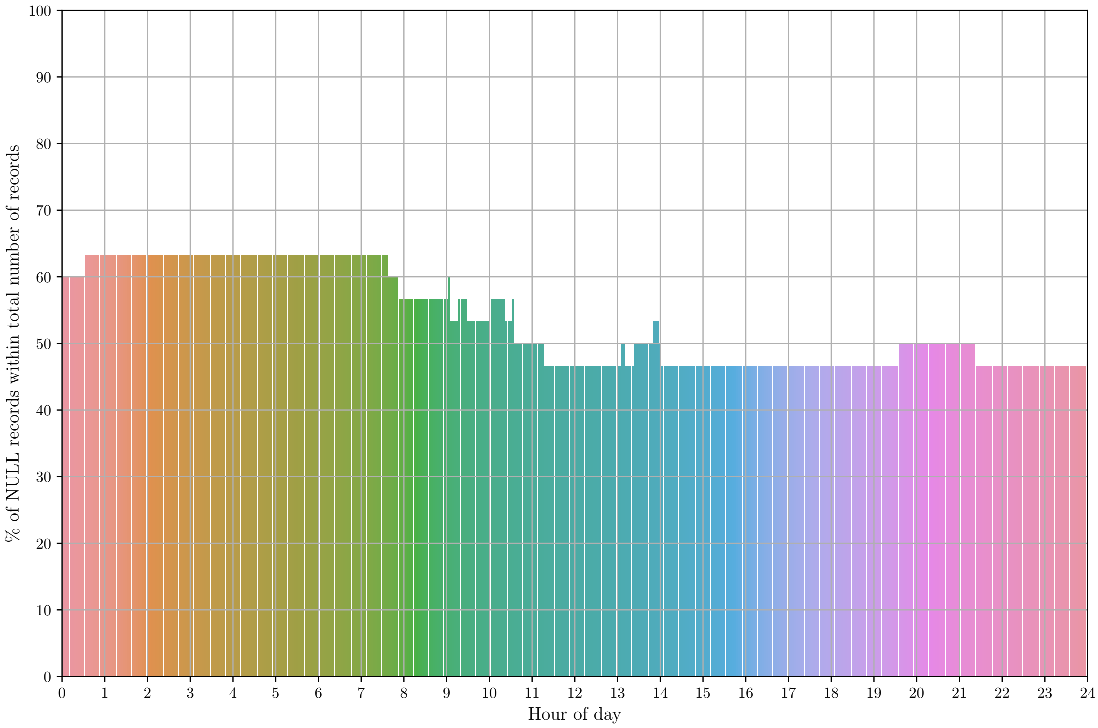

Figure 4.3 – Traffic count station 0214Q01. Data Availability over reference period, per t_{03min} interval.

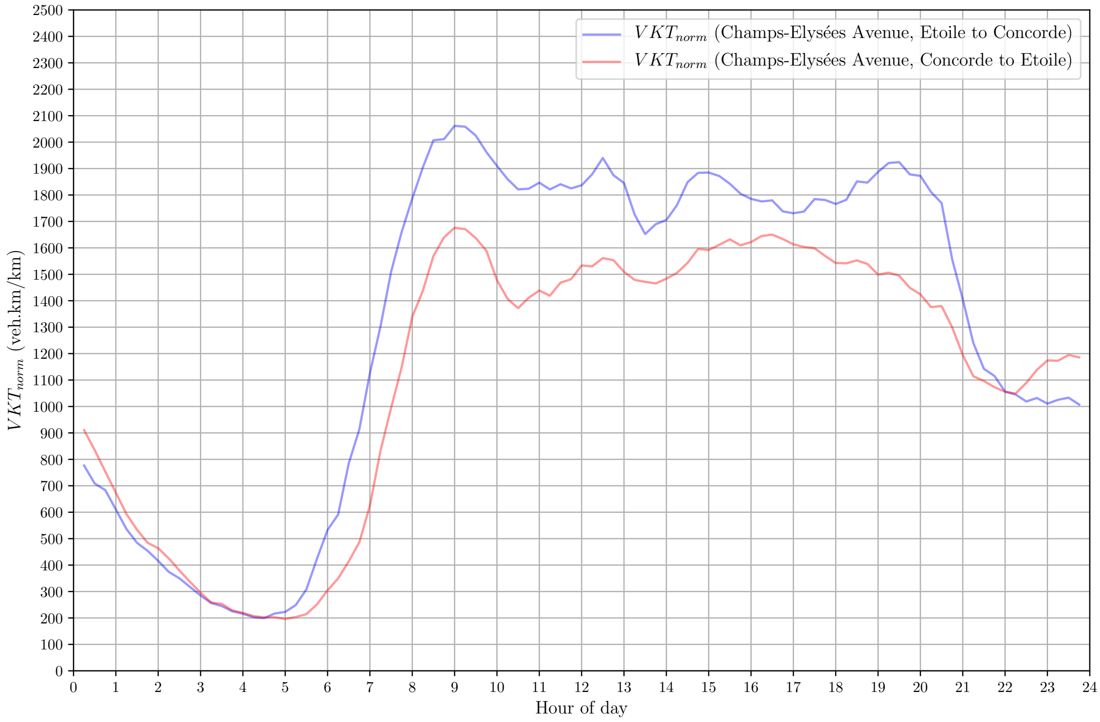

Figure 4.4 – Champs Elysées. VKT_{norm}.

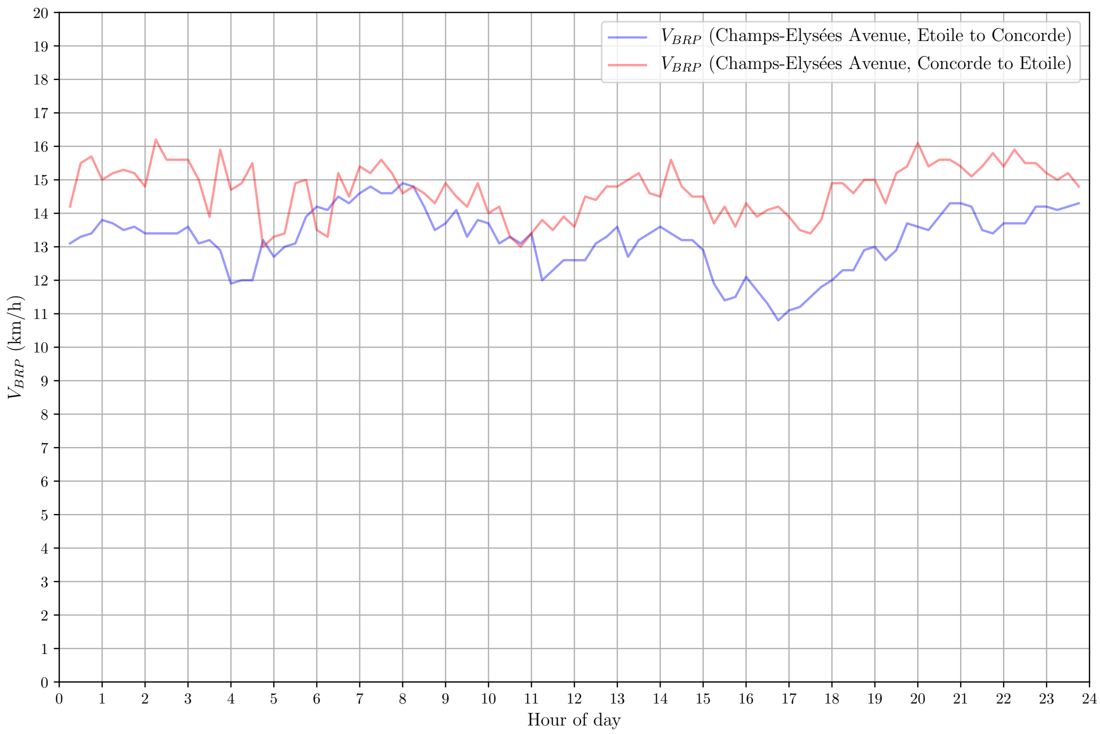

Figure 4.5 – Champs Elysées. V_{BRP}.

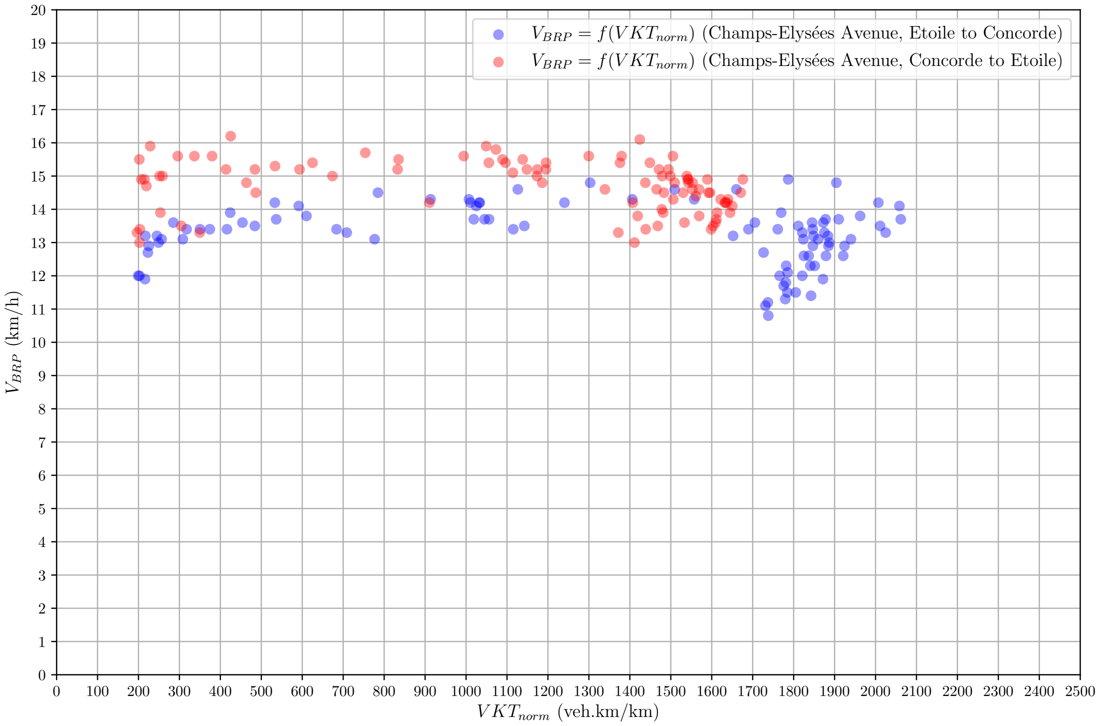

Figure 4.6 – Champs Elysées. $VKT_{norm} = f(V_{BRP})$.

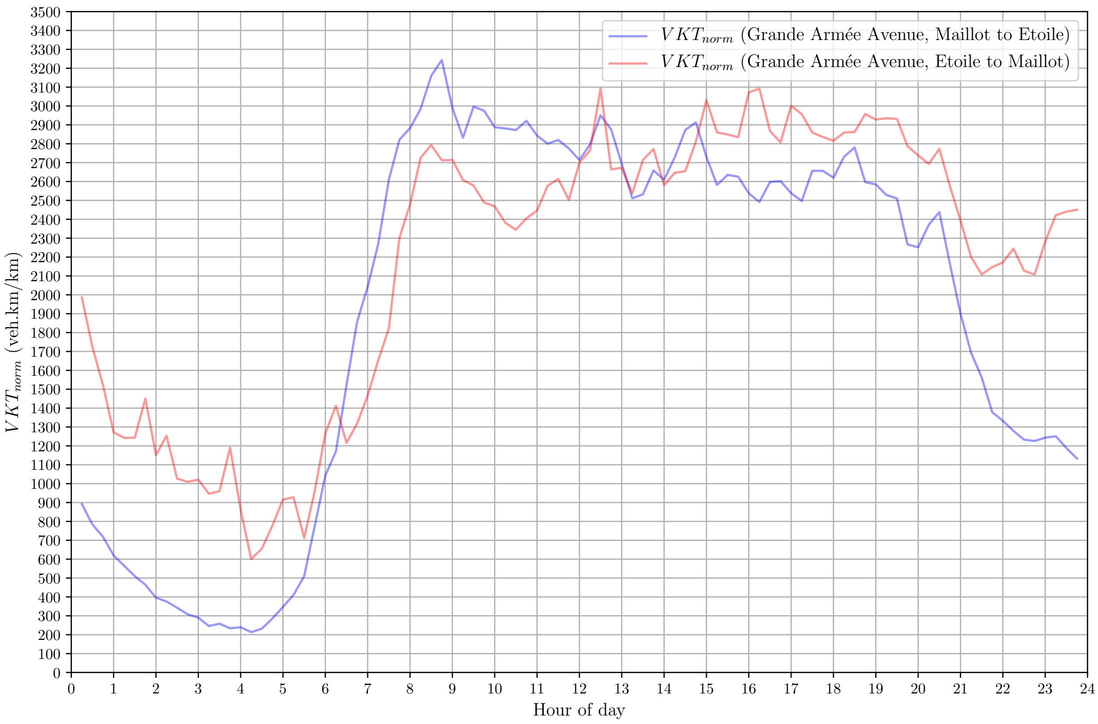

Figure 4.7 – Grande Armée. VKT_{norm}.

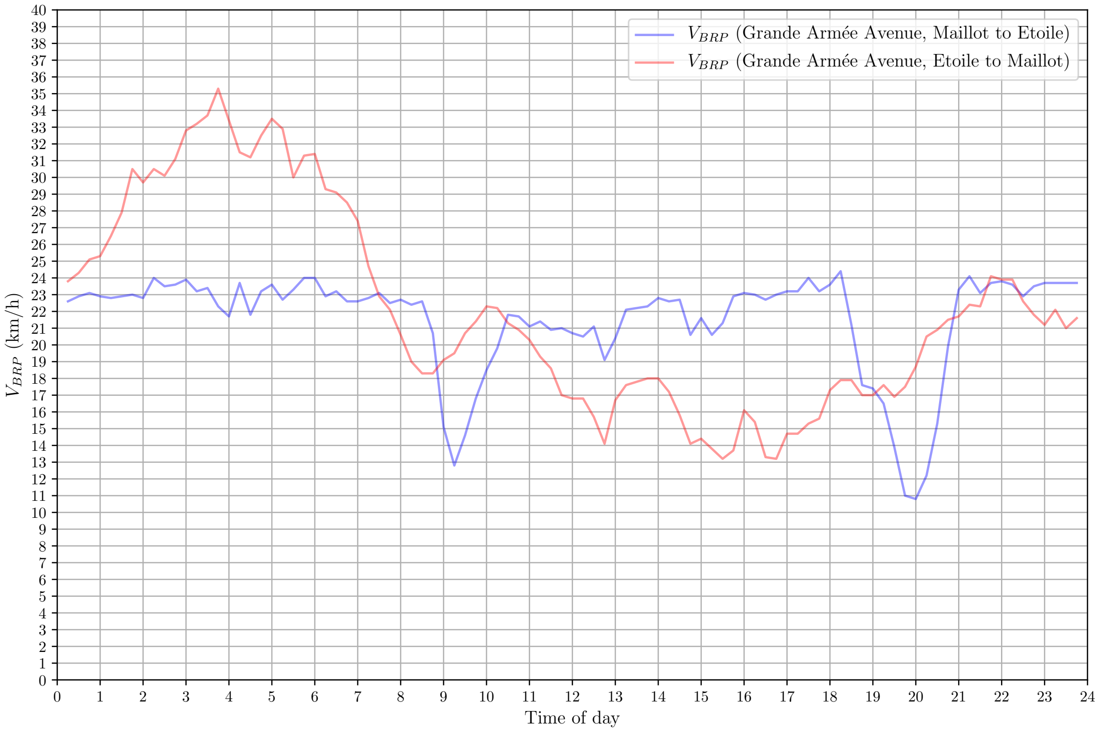

Figure 4.8 – Champs Elysées. V_{BRP}.

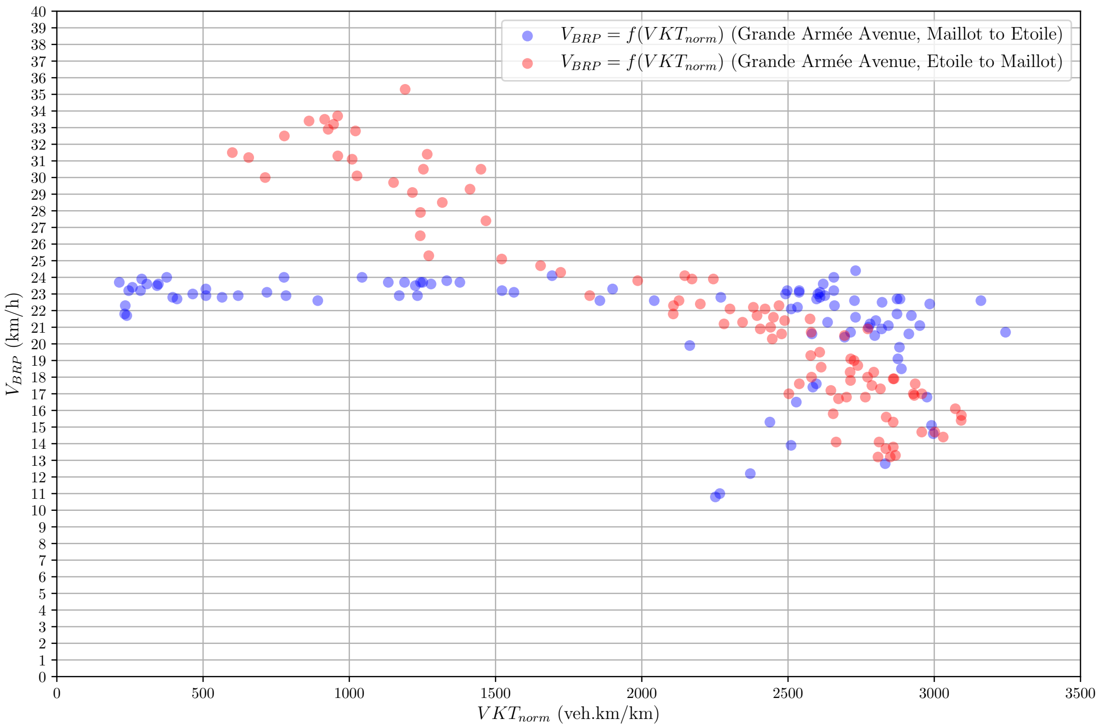

Figure 4.9 – Grande Armée. $VKT_{norm} = f(V_{BRP})$.

4.3 The Bluetooth technology to estimate travel-time

This section provides theoretical and technical background on the Bluetooth collection of travel-times. It defines the terminology to be used throughout the experiment.

A so-called "Bluetooth beacon" is in fact a computer linked to an antenna scanning various frequencies used by the Bluetooth wireless protocol, over an area of circa 100 meters around its location. This "detection range" or "detection area" can then be tuned either by the antenna type (omnidirectional vs. directional) or antenna power (lowering the power lowers the distance covered by the scan).

"Equipments" (these may be smartphones, hands-free sets, onboard computers, laptops, etc.) with activated Bluetooth connectivity that enter its detection range are "detected" by the beacon, which then collects its MAC address. Each detection is timestamped.

The elementary data provided by a beacon B typically consists of a triple of three values $B(a;t;e)$, also called a "record", each being the result of an equipment detection:

- a: the MAC address of the detected equipment;
- t: the timestamp t of the instant at which the detection occurred;
- e: the equipment type (deduced from the MAC address).

It can easily be deduced from these elements that once several beacons are in place, joining the triples $B(a;t;e)$ across different beacons B allows to compute the travel time between them. Formally speaking, if we have two beacons B_1 and B_2, they define an origin-destination pair $(B_1, B_2) = B_1B_2$. The origin-destination pair is itself made of a set of physically possible routes.

Say a MAC address a is detected at time t_1 within the detection range of B_1 and at time t_2 within the detection range of B_2, the travel-time $\Pi(B_1B_2, a)$ of the equipment a traveling on origin-destination (B_1, B_2) is:

$$\Pi(B_1B_2, a) = t_2 - t_1 \tag{4.3.1}$$

For a given origin-destination pair, it is often required to discriminate competing routes. This is typically the case considered here, with two competing routes, one through the roundabout, the other through the tunnel. Discriminating distinct routes r allowing the same origin-destination B_1B_2 can be done in several ways, among which two major can be hinted:

- installing an additional beacon on one of the routes (the somewhat "bulletproof", costly option, which was put in place for this specific experiment);
- identifying, on the general origin-destination pair travel-time distribution, eventual underlying distributions highlighting the various routes.

Data from each beacon is then sent, thanks to GPRS connectivity, to Néavia's servers where it is stored and associated into origin-destination travel-times.

A few technical issues arise when looking at data coming from individual beacons: the first one being that a beacon scans its detection area at a very high rate, which means, since the said detection area often spans over several hundred meters, a given MAC address may be detected more than once. Hence, in the dataset transmitted by a given beacon B, a same MAC address a of an equipment of type e might appear several times within a given time range Δt, as a set of records $B(a;t_{a,1};e), B(a;t_{a,2};e), \cdots, B(a;t_{a,i};e)$ with $t_{a,i} \in \Delta t$.

To solve this, a proprietary Néavia algorithm, on the server, will in the end select, per beacon B, for a given address a and for a given time range Δt, within the set of records $B(a;t_{a,i} \in \Delta t;e)$, the appropriate record $B(a;t_{a,ref};e)$. The algorithm seems to work with the strength of the signal emanating from the equipment and detected by the beacon.

Then, to compute the travel time $\Pi(B_1B_2, a)$ of equipment a between B_1 and B_2, records

$B_1(a; t_{a,ref}, e)$ and $B_2(a; t_{a,ref}, e)$ are joined by their common MAC address a, and:

$$\Pi(B_1 B_2, a) = B_2(t_{a,ref}) - B_1(t_{a,ref}) \tag{4.3.2}$$

The travel-time table for a given route between a beacon B_1 and a beacon B_2 consists in a set $(a, e, t_1, t_2, \Pi(B_1 B_2, a))$:

- a: the (anonymized through a hash-function) MAC address of an equipment detected by both beacons B_1 and B_2;
- e: the equipment type (deduced from the MAC address);
- t_1: the detection timestamp of a at B_1 retained by the algorithm;
- t_2: the detection timestamp of a at B_2 retained by the algorithm;
- the computed travel-time $\Pi(B_1 B_2, a)$, as the delta between t_1 and t_2, following equation (4.3.2).

Now, the next main point is that such a system yields a travel-time for an identified equipment, whose nature is somewhat known. Nonetheless, we have no idea how that equipment is moving. It may be onboard a surface transit vehicle (bus, tram), in a car (private or taxi), on a bike, on someone walking, ...

The Bluetooth travel-time relies on the timestamped detection of the MAC address of Bluetooth-enabled equipments that pass within the detection range of dedicated beacons scanning the Bluetooth frequencies. For an origin-destination pair between a beacon B_1 and a beacon B_2, this yields a table of travel-time records. Each travel-time Π is associated to an anonymized MAC address a, an equipment type e and the reference timestamps t_1 and t_2 selected for each of the two beacons.

4.4 Setting up the Bluetooth beacons and gathering the first data

This section describes the setup of the four Bluetooth beacons that were installed to answer the operational questions regarding the selected origin-destination travel-times. It describes the process that was followed and the encountered hurdles, and how it ultimately led to a satisfactory installation, especially regarding the discrimination of the tunnel and surface routes for the Champs Elysées to Grande Armée origin-destination pair.

It allowed to collect reference data, i.e. with the tunnel still opened to traffic. First results of the traffic patterns on the Place de l'Etoile could be obtained.

4.4.1 Setting up the Bluetooth beacons

The Bluetooth beacons had to be set up as to allow travel-time measurements for the following origin-destination pairs, as illustrated in Figure 4.10:

- Champs Elysées to Grande Armée through the tunnel, in order to have a travel-time estimate before the tunnel closure;
- Champs Elysées to Grande Armée through the surface, via the traffic circle;
- Grande Armée to Champs Elysées via the traffic circle;
- Grande Armée to Friedland, as additional traffic coming from the Champs Elysées on the surface after the tunnel closure could mean harsher conflicts with vehicles traveling from Grande Armée towards Friedland.

Wagram and Foch are also heavily traveled avenues, nevertheless, due to the limited funding available, they were not be equipped with Bluetooth beacons.

From the first meeting with Néavia, right before Summer 2014, to the effective installation of the beacons around the Place de l'Etoile on September 18th, 2014, several weeks passed.

That period of time allowed to prepare the installation process, based both on standard procedures issued by Néavia regarding the beacons setup, and on mandatory regulations for the maneuvers and personnel involved in the installation campaign.

The first step was to identify the streetlight poles on which the beacons were to be installed. The following factors had to be taken into consideration: limiting to a minimum detection obstacles (especially trees, and that is a real issue since Paris main avenues are all planted with trees), making sure the pole is reachable by the required vehicles (especially the motorized safety cradle), and that the pole is visually in good state (to be confirmed through mechanical analysis by a specialized contractor).

The preparatory work led to the installation, supervised by the author, of the four Bluetooth beacons around the Place de l'Etoile, on September 18th, 2014. The operation lasted from 08:00 to 15:00. Originally planned to last about three hours, the operation was delayed as one beacon's printed circuit board had been damaged when held up in the air to be strapped to its streetlight; fortunately a spare part was available and replacement of the faulty circuit was done on-site by Néavia's engineers.

All beacons were installed on streetlight poles. Each of them was connected to the electrical feeder of its respective streetlight. The beacons run on batteries during the day, and are charged during the night when the feeder is live to power the streetlight.

Three beacons were positioned on the three arterials studied, one per arterial (Grande Armée, Champs Elysées and Friedland). They were equipped with 360-degree antennas, whose range allows to collect MAC addresses from equipments traveling in both directions (either going towards or away from the Place de l'Etoile) of the studied roads.

In order to discriminate the two competing tunnel and surface itineraries on the Champs Elysées to Grande armée origin-destination, a fourth sensor was installed above the inbound tunnel ramp. Instead of a 360-degree antenna, it was equipped with a directional antenna, as to collect signal solely (at least as much as one can hope) emanating equipment moving on the tunnel's entrance ramp.

The standard setup process for a single beacon can be summarized as follows. From the author's perspective, it blatantly illustrates the fact that on operational grounds, the deployment of such non-intrusive devices, that makes use of existing infrastructure and that at first-sight appears to be a "simple", or say a "trivial" operation, is in fact a long, laborious process. Many parties are involved: two divisions of the Direction de la Voirie, with the author, from the PCE Lutèce, and a technician from the streetlight division, two engineers from the beacon's providers, and three technicians from EVESA, the City's private contractor for streetlights and traffic lights maintenance.

- streetlight poles mechanical resistance has to be checked before installing the sensors, since adding a device weighing even a few kilograms high on a pole increases the mechanical stress exerted on it;
- GPRS connectivity on the site has to be checked for consistency, as the collected data is transmitted through the standard cellular network to the provider's server;
- a cradle is required for the workmen to install the sensors about ten meters above ground, in order to maximize the detection range and put the sensor out of people's reach (fear of

vandalism);

- the sensor is strapped to the pole with two iron straps;
- a power cable then needs to run along the pole from the sensor down to the inspection hole at the bottom of the streetlight, through which it goes to get power (as this is a temporary set up, drilling the pole and running the power cable inside it would have compromised the watertightness of the streetlight pole and the integrity of the electrical equipment it houses);
- high traffic volumes increase pressure on the temporary work-sites, as blocking a traffic lane even off-peak lead to local traffic disturbances.

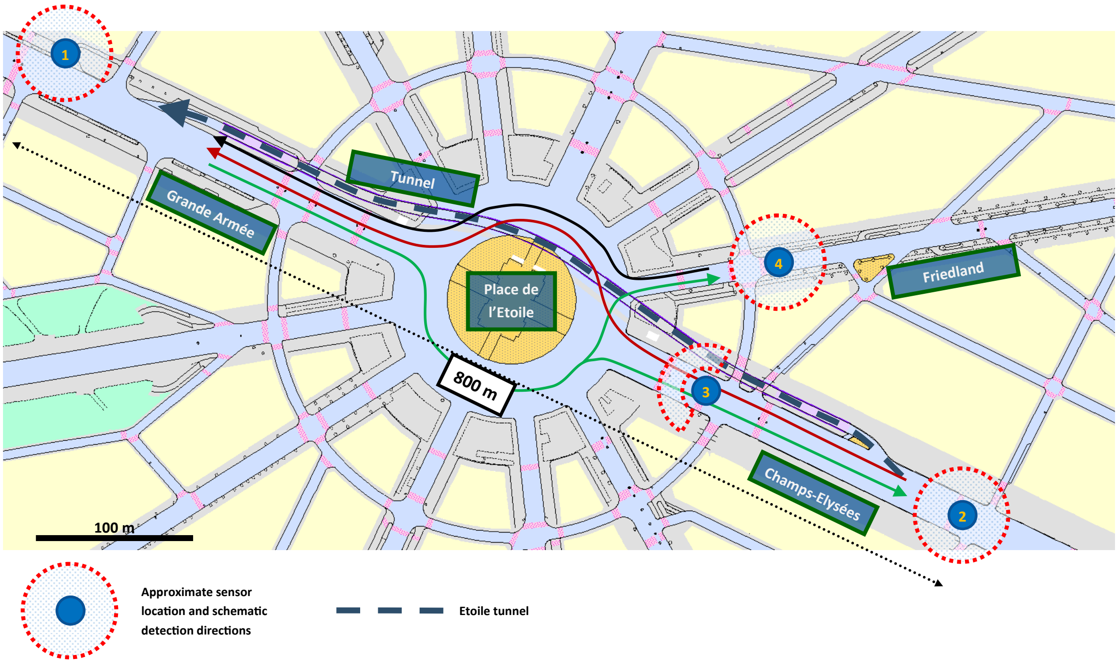

Figure 4.10 – Place de l'Etoile map. Approximate sensors location and beacon antennas directions. Arrows represent the studied turning movements.

4.4.2 Gathering "reference" data and first observations

After the original September 18th setup, a few adjustments had to be made.

The strategy adopted to discriminate between the surface and tunnel routes on the Champs Elysées to Grande Armée origin-destination had to be overhauled. In the original setup, the beacon was installed with its directional antenna meant to catch equipments using the tunnel's ramp. After a few days, a first investigation of the collected data showed suspicious "surface-like" travel-times were still observed on the tunnel route travel-times. In other words, even though the tunnel was almost never congested, travel-times turned up to be largely pessimistic[3].

The beacon's directional antenna orientation and configuration was at first questioned, but the detection area was corresponding to the tunnel entrance ramp. Traffic staying on the surface route shouldn't theoretically have been detected at rates observed in the dataset. Of course, a

[3]Unfortunately, data and plots made at the time have not been backed up and therefore cannot be shown here.

Figure 4.11 – Cradle and workmen installing beacon B_2 on a streetlight pole on the Champs Elysées.

100 % correct match of vehicles on the tunnel or surface route couldn't be attained, but higher travel-times should have been marginal, included in the tunnel travel times distribution's tail.

In the end, it turned out the site's layout was the culprit. The Champs Elysées is bordered on its north side by a 20 m large sidewalk (from the bordering buildings facade to the curb). The streetlights are installed along the curb. The two-lane tunnel's entrance ramp branches off the Champs Elysées, and its right-of-way takes half the sidewalk's width (which is then reduced from 20 m to 10 m), and steeply dives into a trench. The ramp itself is circa 80 m long between its origin on the Champs and the tunnel's mouth. The beacon was 20 meters away from the facades, but as its antenna was oriented toward the tunnel's ramp, it directly faced the facades. Bluetooth signals of the equipments and scanning signals of the beacon were bouncing on the facades, meaning that a MAC address detected by the beacon could have emanated from an equipment traveling on the surface route.

The proposal made was to fine tune the travel-time algorithm and the beacon's firmware, but the author chose another approach: the pole on which the beacon was installed was changed, so as to catch the surface route: instead of trying to catch traffic traveling the tunnel ramp, we would measure equipments traveling on the surface. The beacon was moved downstream towards the plaza, after the tunnel's entrance, so as to solely catch equipments on the surface route. The antenna was oriented away from the facades, in the direction of the roadway itself. This involved additional cost as a new streetlight had to be tested for mechanical resistance, and material and personnel mobilized for an hour to get the beacon down its original position and up on its new one.

Another, smaller issue was dealing with a local power outage on a beacon due to improper connection of the feeder.

Figure 4.12 – Zoom on beacon B_4 on Friedland Avenue.

The setup was considered "bulletproof" by mid-February, 2015. Thus, the timeframe for the so-called "reference period" (i.e., the tunnel being opened) runs from February 1st, 2015 to March 15th, 2015, the tunnel closing on March 16th. All studies were carried on business days data (Monday to Friday, weekends excluded).

The choice was made not to exclude specific days (like periods of occasional closures of the tunnel due to a strucked vehicle, or of demonstrations during which traffic may be restricted), as the length of observation and the amount of data gathered guarantees a "stability" in the

Origin	Origin Records Number	Destination	Destination proportion
Champs Elysées	182,573	Friedland	9 %
		Grande Armée par surface	31 %
		Grande Armée par tunnel	60 %
Friedland	53,615	Champs Elysées	27 %
		Grande Armée	73 %
Grande Armée	183,891	Champs Elysées	78 %
		Friedland	22 %

Table 4.1 – Origin-destination proportions during the reference period, for the place de l'Etoile avenues equipped with Bluetooth beacons.

observed travel-times distributions.

Travel-time studies are carried out on the three following routes:

- Champs Elysées to Grande Armée through the tunnel;
- Champs Elysées to Grande Armée through the surface;
- Grande Armée to Friedland.

4.4.3 O-D patterns as shown by the Bluetooth detection

One of the first applications of the installation was to quantify the turning movements already identified by experience. The process is quite straightforward: for the different OD pairs, records are counted by origin, and then for each origin, by destination. Results are shown in Table 4.1.

The results presented here cover the whole reference period. More detailed analysis was made for morning and evening peaks.

The importance of the tunnel in East-West movements across the plaza is confirmed. 60 % of the records on the Champs Elysées and bound for either Grande-Armée or Friedland are recorded through the tunnel. Simply considering the origin-destination from Champs Elysées to Grande Armée, thus excluding the Champs Elysées to Friedland route, two-third of the records are through the tunnel.

4.4.4 Type of equipments distribution on the global dataset (all routes)

A MAC address allows to classify the equipment bearing it. Figure 4.14 shows records count per identified category of equipment over all origin-destination pairs.

Two categories of equipments stand out: the Audio/Video category, with hands-free devices and wearable headset devices subcategories, followed by phones, with cellular and smart phones subcategories. Other categories remain negligible.

In other words, Bluetooth-paired wireless audio devices are the main contributor to the collected data, followed by phones.

The section showed that the urban context presents hurdles to an apparently simple process: installing temporary beacons upon streetlight poles. For "only four" beacons, three stakeholders were involved: the beacons provider, the streetlights maintainer, and the City of Paris. Side effects from the environment can sometimes hardly be anticipated, as shown by the issue of the signal bouncing observed on the surface-tunnel discriminating beacon.

The first analysis shows that the beacons can also yield origin-destination patterns, completing the travel-time information they provide.

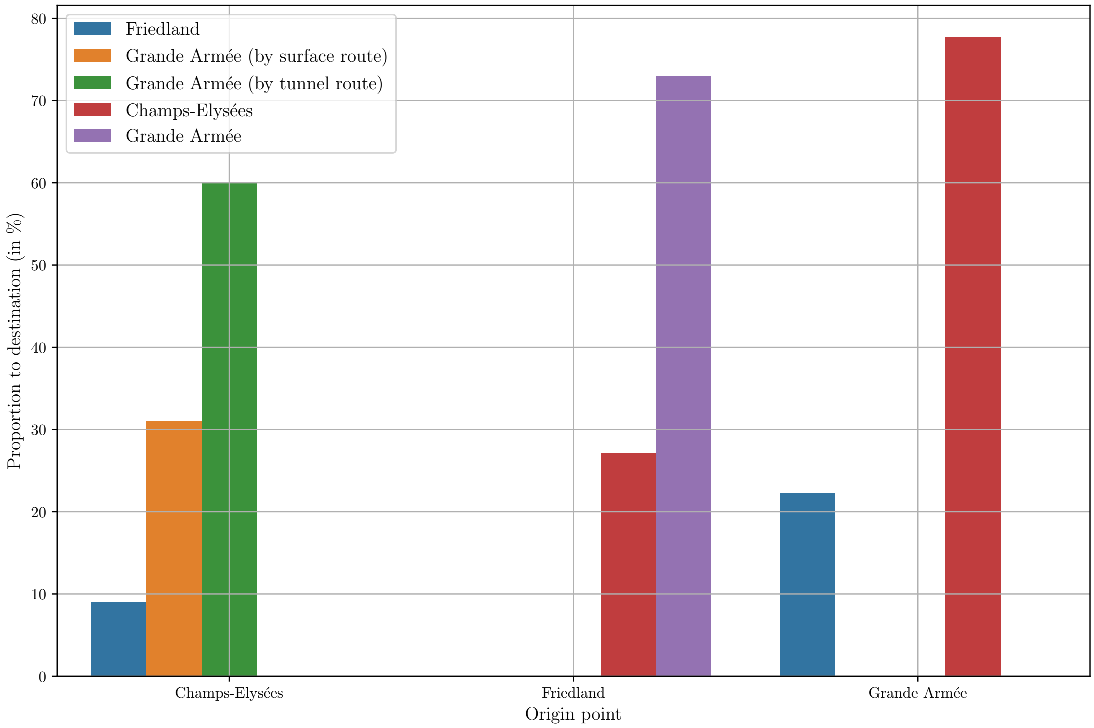

Figure 4.13 – Destination proportions per origin

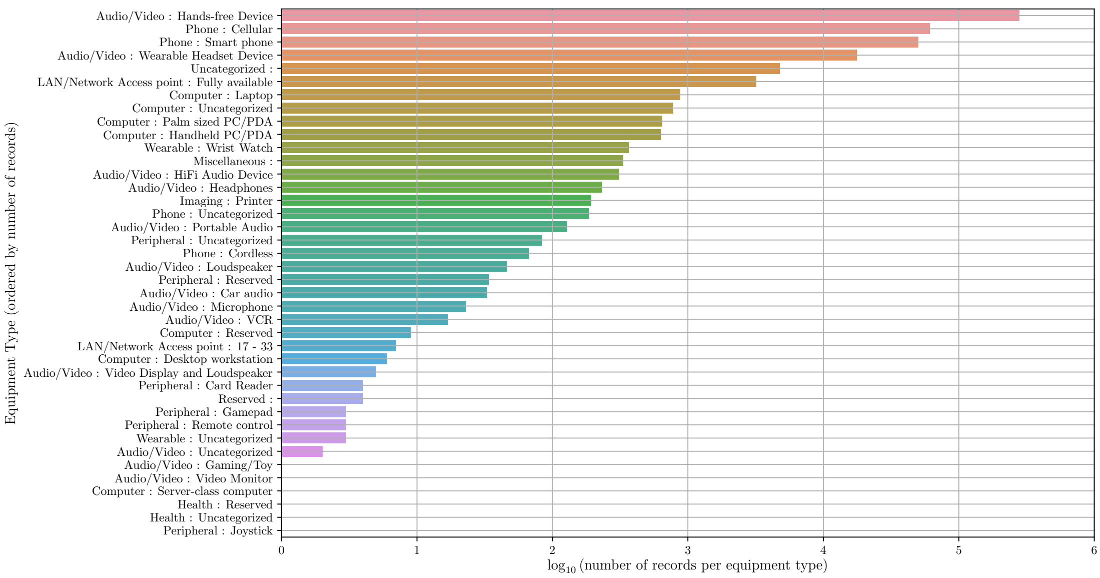

Figure 4.14 – Equipment types recorded during the reference period over all OD pairs

The population of equipments detected includes a variety of categories, of which two main stand out: wireless audio devices and phones. One of the questions that arises is whether these equipment types say anything about the mode of travel they're being carried with (pedestrians, vehicles), and how travel-times are distributed when considering these two main equipment categories. The latter analysis will be carried out on the Champs Elysées to Grande Armée origin-destination pair.

4.5 The Champs Elysées to Grande Armée route: investigating the properties of the Bluetooth travel-times

There are two competing routes (through the tunnel or by the surface) to go from the Champs Elysées to Grande Armée. The study of these two competing routes is one of the operational issues the experiment addresses. It is also a great field to investigate several aspects of the Bluetooth travel-times, namely the compared volumes of Bluetooth equipments and vehicle counts from the traffic loops, and whether the equipment types discriminate travel-time distributions.

4.5.1 Records count

In order to grasp the dynamics in terms of volumes of information, as we deal here with Eulerian (fixed) road-side sensors, the evolution of the number of records with respect to time is plotted and analyzed.

For Bluetooth data, a record is understood as a MAC address with entrance (at beacon B_2 on the Champs Elysées) and exit (at beacon B_1 on Grande Armée) timestamps and the associated travel-time.

For traffic loops data (also called "SURF data"), a record is understood as the detection of one vehicle on the loops located just before arriving at the traffic circle. In other words, if n vehicles are counted during Δt, there are n records for that period.

The records counts are computed as follows:

1. time t is divided into 3 min slots over the reference period (independently of day), i.e., if t is expressed in epoch, the time basis t_{03min} over which records are counted is:

$$t_{03min} = (t \bmod (24 \times 3600)) \text{ div } (3 \times 60)$$

2. over each t_{03min}, the records are counted (independently of day).

The length of 3 min was chosen because it is the smallest time aggregation at which loops' data is archived on the Paris network.

Traffic loops data clearly shows (Figure 4.15) the temporal dynamics of East-West traffic flow. Traffic volume is at its lowest between 03:00 and 05:00, and then begins to rise after 05:00 with a very steep increase between 06:30 and 08:00. There is a very sharp morning peak, after which the traffic volume quickly decreases to meet its daytime lowest around 11:00. The afternoon sees a more gradual increase of traffic, peaking around 19:00, but without reaching the morning levels. Occupancy values and travel-times will give an insight on the effective congestion at this time of day. After 20:00, traffic decreases, with a small peak around 23:00 (explained by the night-life of the Champs Elysées area), and then past 23:00 decreases through the night.

For Bluetooth data (Figure 4.16), the total records number per t_{03min} slot varies between 30 and 500 for the whole period. The dynamics shown, even if the number of records is far lower than the loops, closely resembles what has been observed on the traffic counter, with a very sharp morning peak and a more spread evening peak, reported here by an increase in the number of travel-times records.

Note that it is difficult to deduce a Bluetooth penetration rate from the data. Traffic counted by the two traffic sensors on Champs Elysées just before the plaza doesn't necessarily aim at Grande Armée (at least for the part of traffic counted on the surface route), whereas Bluetooth data is only recorded for the part of equipment traffic that effectively crosses the plaza between Champs Elysées and Grande Armée.

Finally, loops and Bluetooth records data is compared on the same plot. Data has been independently normalized for each dataset (Bluetooth and traffic loops) as follows: for a dataset, let n_i be the number of records over a given t_{03min} period i. n_i is normalized as $n_{i,norm}$ relative to the minimum and maximum number of records in the dataset over the whole set of t_{03min} periods (i.e., 24 hours):

$$n_{i,norm} = \frac{n_i - n_{min}}{n_{max} - n_{min}}$$

Once normalized, it is remarkable to see how "Bluetooth volume" relates to "loops volume", more specifically on the tunnel route. For the surface route, there are greater gaps, which remain to be explained. A plausible assumption would be that during peak hour, vehicles that cannot take the tunnel are not much equipped with Bluetooth-enabled devices.

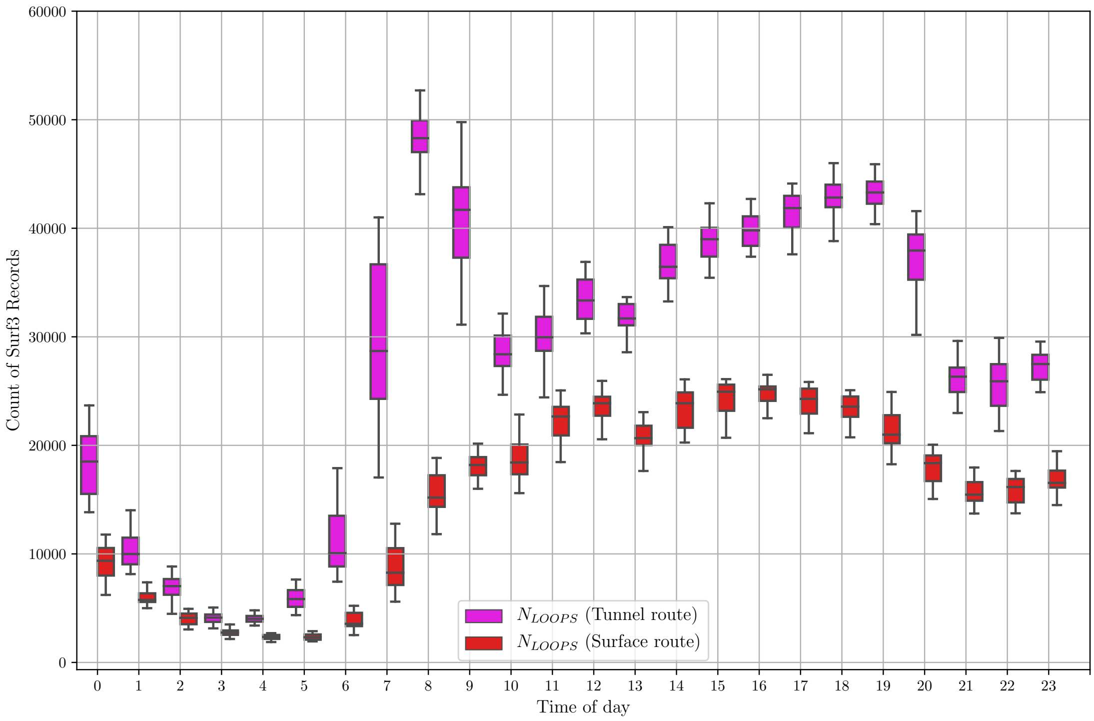

Figure 4.15 – Traffic loops records count per t_{03min} time slot: distribution per hour.

4.5.2 Equipment types

The equipment types statistics are consistent, as Figure 4.18 shows, with the results of the global analysis over all OD pairs. Like in the previous case, two categories (or four types) stand out: Audio/Video, with hands-free devices and wearable headset devices types, followed by phones, with cellular and smart phones types. Other categories remain negligible.

4.5.3 Travel-time distribution (general and split by equipment type)

Since the number of significant equipment types is limited to four items, it felt natural to look at the empirical distribution of travel times produced by each type of equipment, considering the surface route, and then the tunnel route.

First, we plot (Figure 4.19) the travel-time distribution per equipment for the surface route. The distribution for three out of the four major equipment types, i.e. hands-free devices, cellular phones and smart phones, constitute a coherent group: the minima, maxima and general shape of

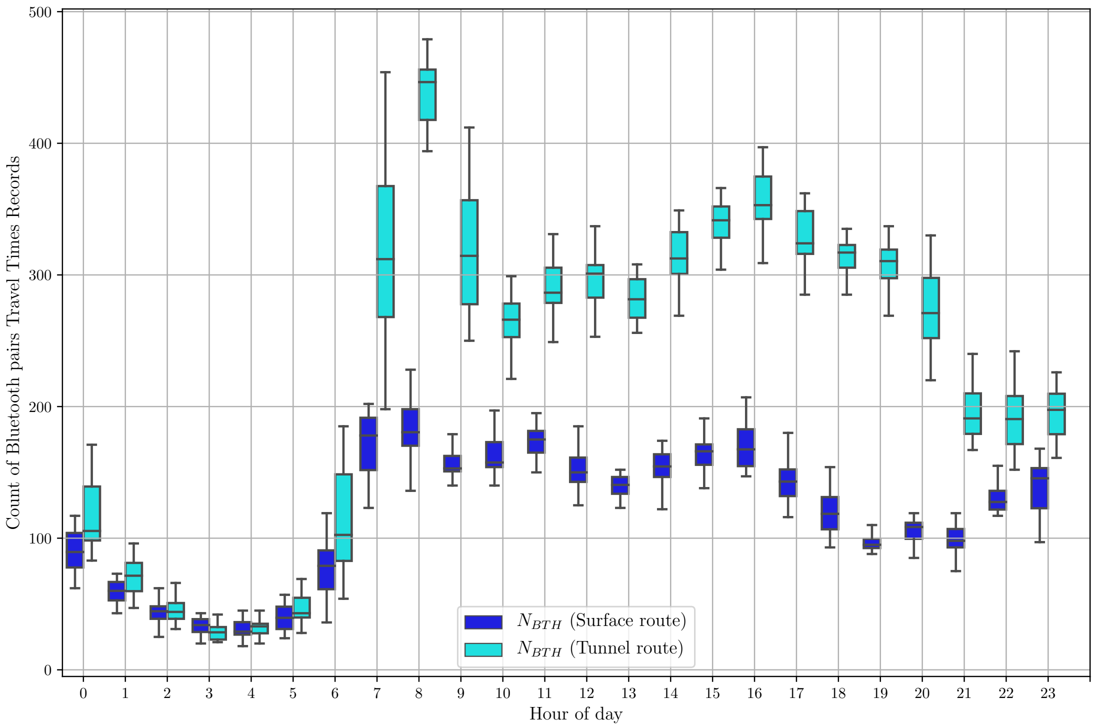

Figure 4.16 – Bluetooth records count per t_{03min} time slot: distribution per hour.

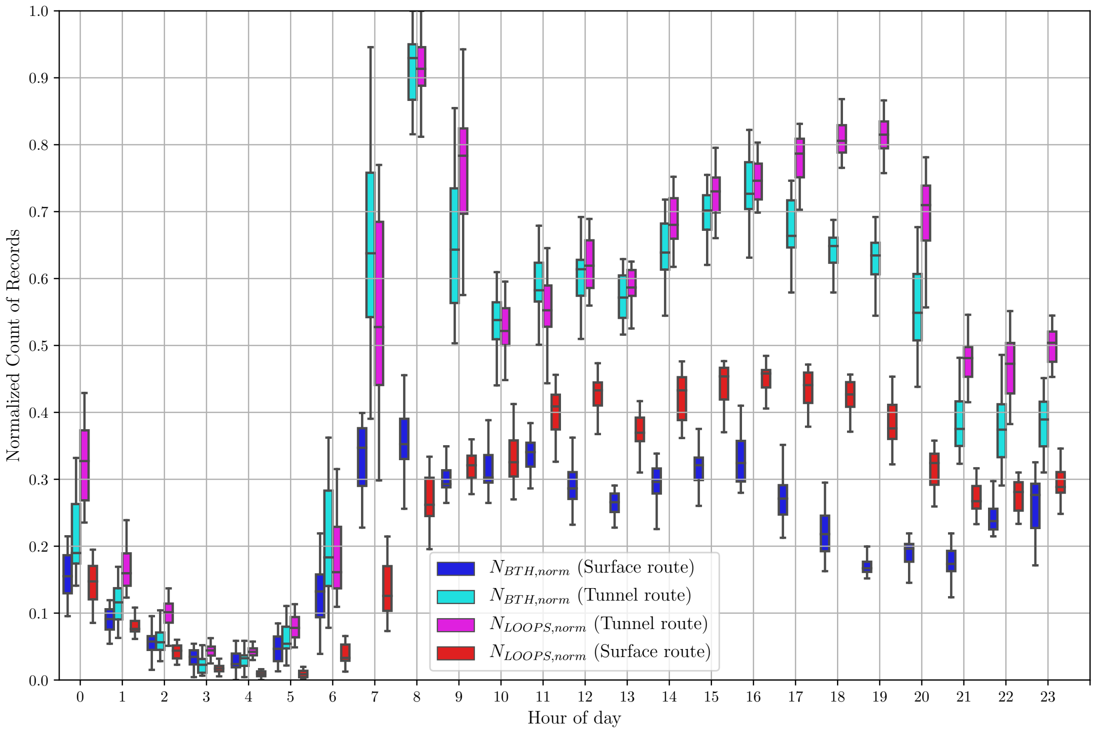

Figure 4.17 – Compared normalized Bluetooth and traffic loops records count per t_{03min} time slot: distribution per hour.

these distribution are consistent with one another, with a median travel-time of 130 s. Their slight differences are mainly accountable to the varying sample size between these three categories, the hands-free device constituting more than half of the records.

The distribution of travel-times for wearable headset devices clearly stands out of the former

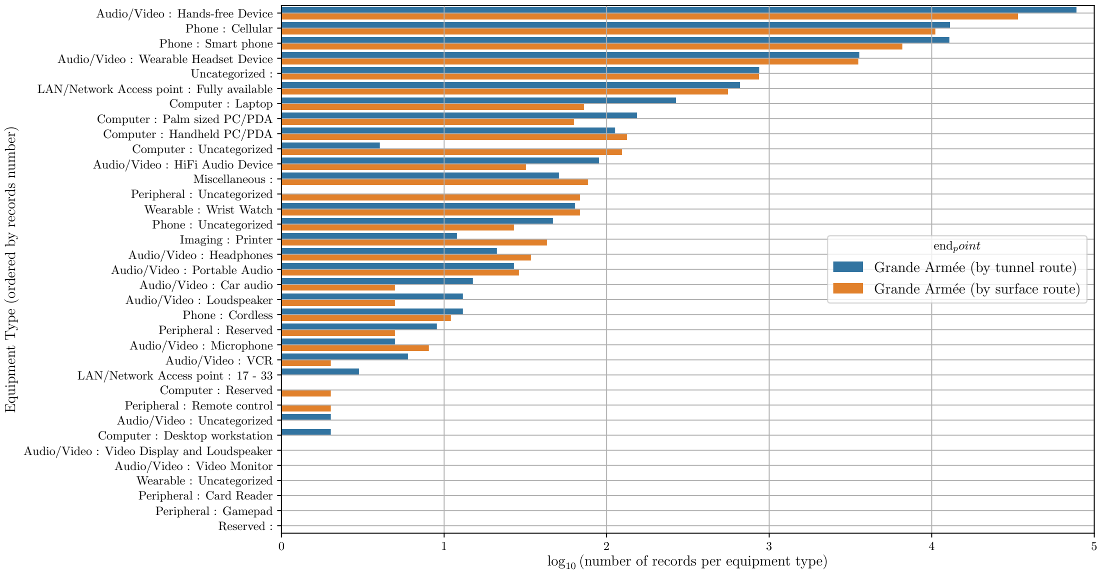

Figure 4.18 – Equipment types recorded during the reference period over the Champs Elysées to Grande Armée origin-destination, over respectively the tunnel and surface routes.

three categories, with a median travel-time of 86 s. This means that these equipments travel twice as fast as the others, which they seem to be able to pass with no hassle.

These clearly can hardly be pedestrians; indeed, before the tunnel's closure, the plaza entrance coming from the Champs Elysées rarely was a gridlock for motorized traffic, and the process of crossing the plaza as a pedestrian is rather tedious as it involves either crossing at grade through uncoordinated (pedestrian-wise) signalized intersections five avenues, or using the pedestrian tunnels of the extensive subway station underneath, with a few stairways and detours.

A specific "four-wheel" vehicle fleet (taxis, buses, ...) wouldn't have room to pass and dig such a travel-time difference with the rest of the traffic, as there is no dedicated bus or taxi lane on this section of the Champs Elysées. Moreover the right lane is often clogged up with abusively parked cars, local delivery vehicles or taxis.

The equipment type, wearable headset device, gives a complementary clue on who might be behind these travel-times: motorized two-wheelers. Cyclists aren't encouraged to take the plaza given its traffic volume, and are diverted to the parallel streets which force them to a halt at each of the five avenues to cross between the Champs Elysées and the Grande Armée, the traffic light coordination being made independently for each of the main avenues radiating out the plaza, in the form of green waves, and not on intersecting local streets.

The tunnel travel-times (Figure 4.20) also shows this discrepancy between the faster "wearable headset device" group and the other equipment types, although the tunnel allowing free-flowing movement between the two beacons, with no traffic light, the gap between the two groups is far lower.

These observations show the complexity of the travel time notion of a flow: general travel-time distributions in fact mix several fleets, and regarding motorized traffic, at least two of them can be differentiated: four-wheelers and two-wheelers.

4.5.4 Travel-time time series

Having investigated the distribution of travel time in terms of values (histograms), let's see how travel time evolves through the course of time. Given the differences highlighted in the

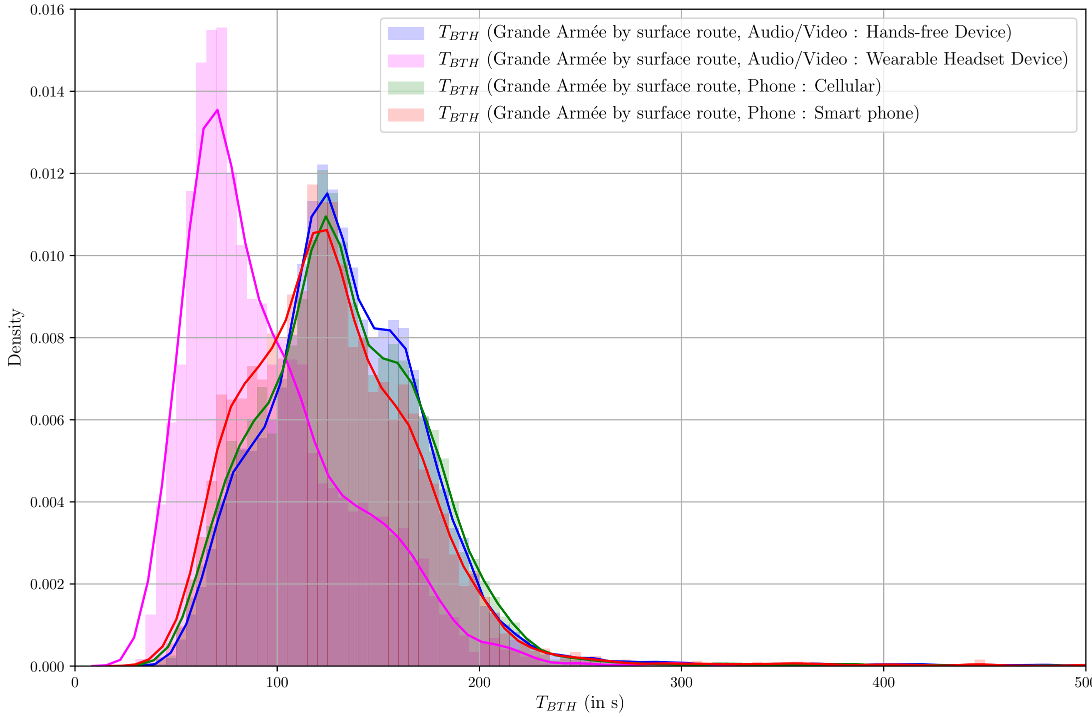

Figure 4.19 – Travel time distribution on the surface route, for the four major types of Bluetooth equipments.

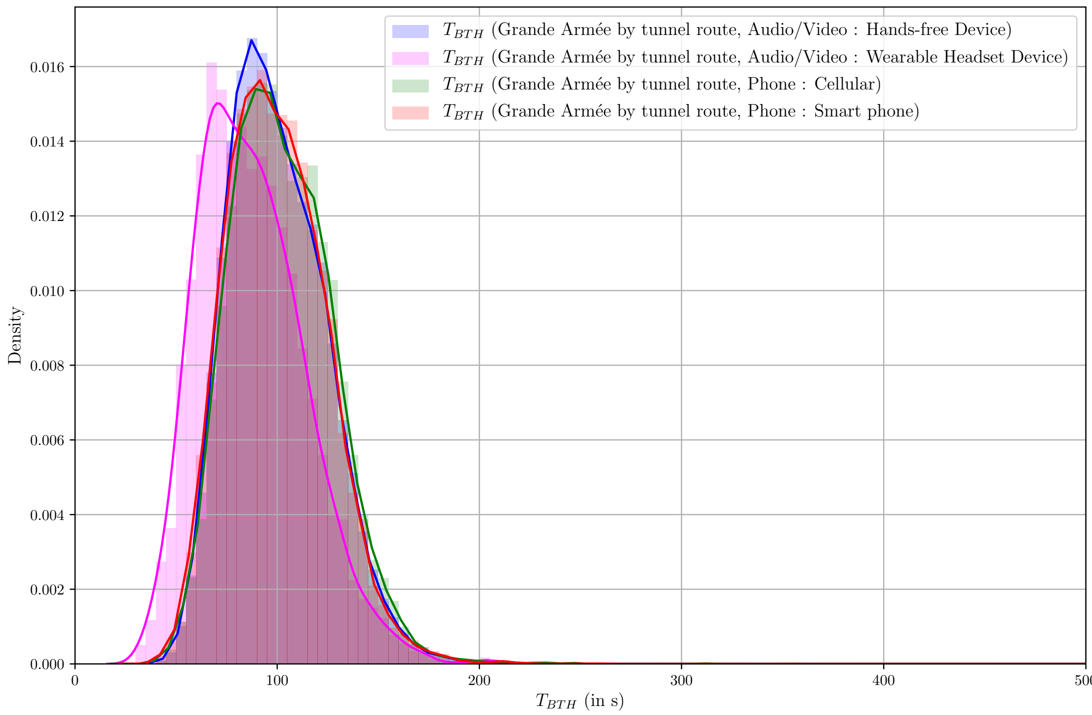

Figure 4.20 – Travel time distribution on the tunnel route, for the four major types of Bluetooth equipments.

previous section, we will consider, for each routes, the following two equipment categories:

- The "phone" category, which includes Hands-free devices, Cellular phones, and Smart phones records;

- The “headset” category, which includes Wearable headset devices.

The median travel time is plotted, function of time, for both equipment categories and both surface tunnel routes. The median is computed over t_{03min} intervals as previously stated.

Looking at the surface route (Figure 4.21), the headset median travel-time is highly scattered at night hours, especially between 00:00 and 06:00. A plausible assumption, confirmed by the records number plots (Figure 4.22), is that there are very few headset records per 3 min slot, making the median extremely sensitive to individual equipment behavior. From 06:00 to 23:00, the headset travel-time, although more dispersed than the phone travel-time, remains inferior (centered around a time of 1 minute) to the phone travel-time (oscillating between 1 min 30 s and 2 min). Note also that the number of headset records remains somewhat constant throughout between 09:00 and 19:00 and doesn't see the great peak and midday variations of the phone group during that same period of time.

The tunnel (Figure 4.24) operates at nearly free flow regime, as shown by the overall low dispersion of travel times distribution. Night (00:00 to 06:00) values remain highly scattered for headsets, again explained by the very low number of records (Figure 4.25 and Figure 4.26). Headset travel time remains more scattered than phone travel time, and slightly lower, nevertheless both median values remain close.

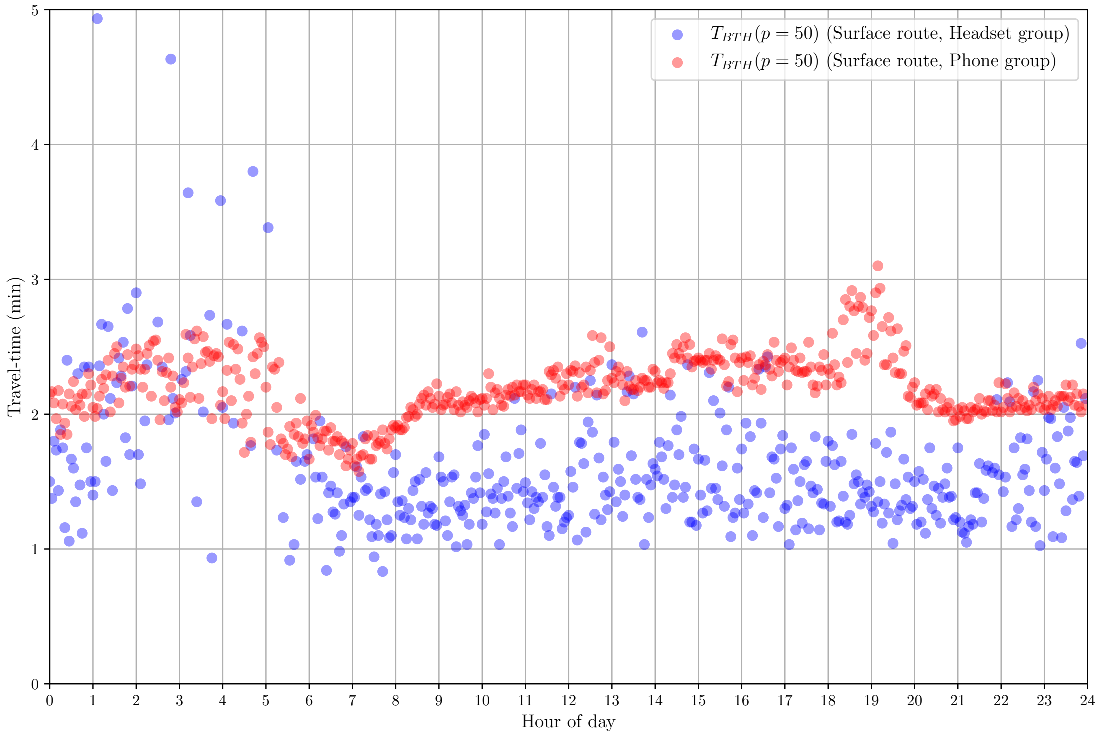

Figure 4.21 – Median travel time time series distribution on the surface route, for the two identified groups of equipments..

4.5.5 A Bluetooth fundamental diagram?

The two previous sections presented records count, and then travel-time, as two distinct time series. The observation of both of these time series hints a relationship between them.

Remember the time over the reference period is split into t_03min intervals, independently of the date:

$$t_{03min} = (t \bmod (24 \times 3600)) \operatorname{div} (3 \times 60)$$

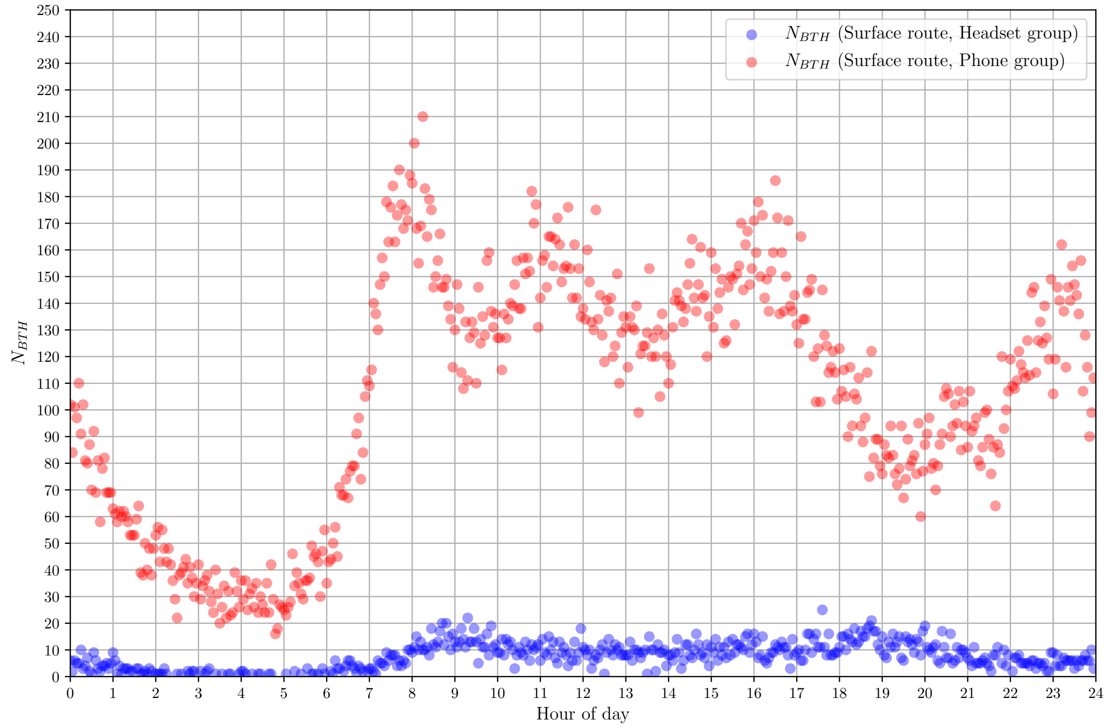

Figure 4.22 – TT records count on the surface route, for the two identified groups of equipments.

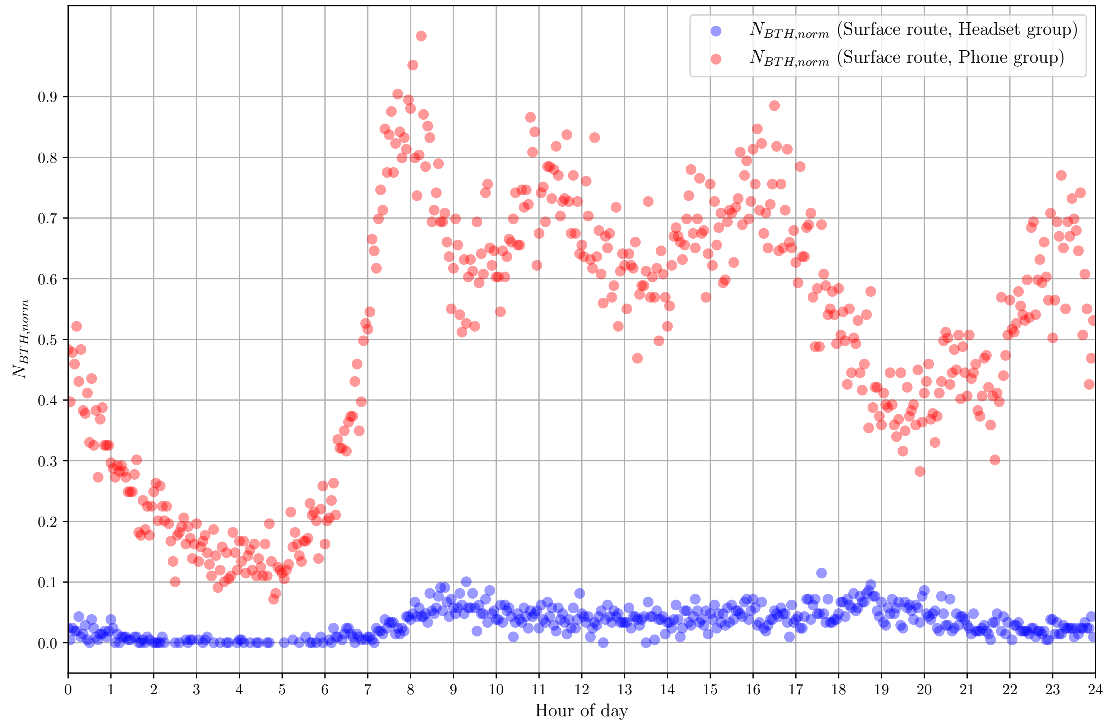

Figure 4.23 – Normalized TT records count on the surface route, for the two identified groups of equipments.

Therefore the set T_{03min} of t_{03min} intervals has a cardinal of 480.

Let N be the set of distinct values taken by the total number of records per t_03mins interval. For a specific value $n \in N$, all values Π of travel-times falling into the t_{03min} intervals with this number of records are selected.

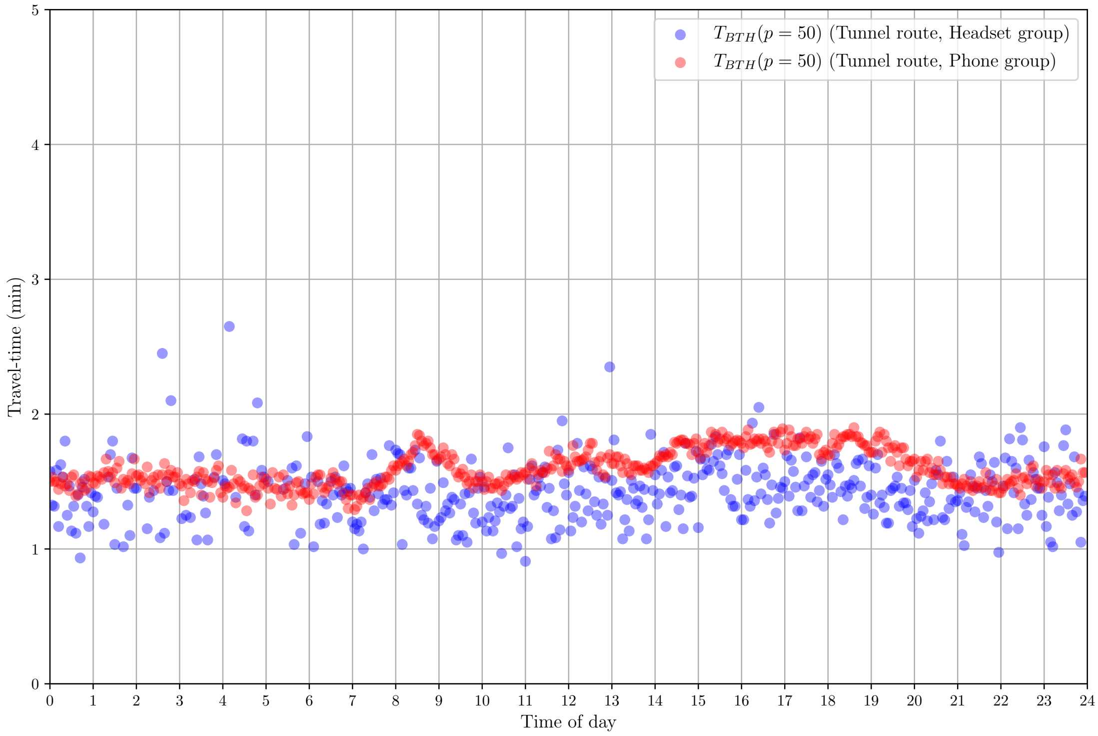

Figure 4.24 – Median travel time time series distribution on the tunnel route, for the two identified groups of equipments..

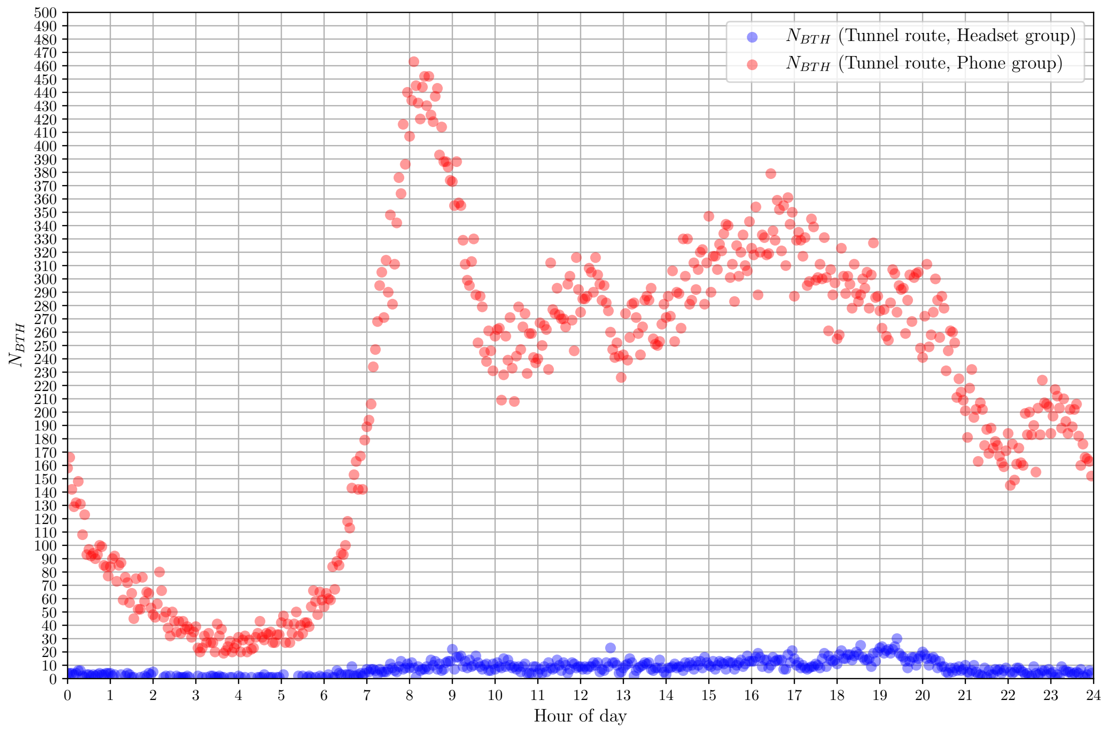

Figure 4.25 – TT records count on the tunnel route, for the two identified groups of equipments.

In a probability theory context, if N is considered as a random variable (values taken by the number of records per t_{03min} interval) and Π is considered as a random variable (the Bluetooth travel-time on a route), the "Bluetooth fundamental diagram" is the plot of the conditional

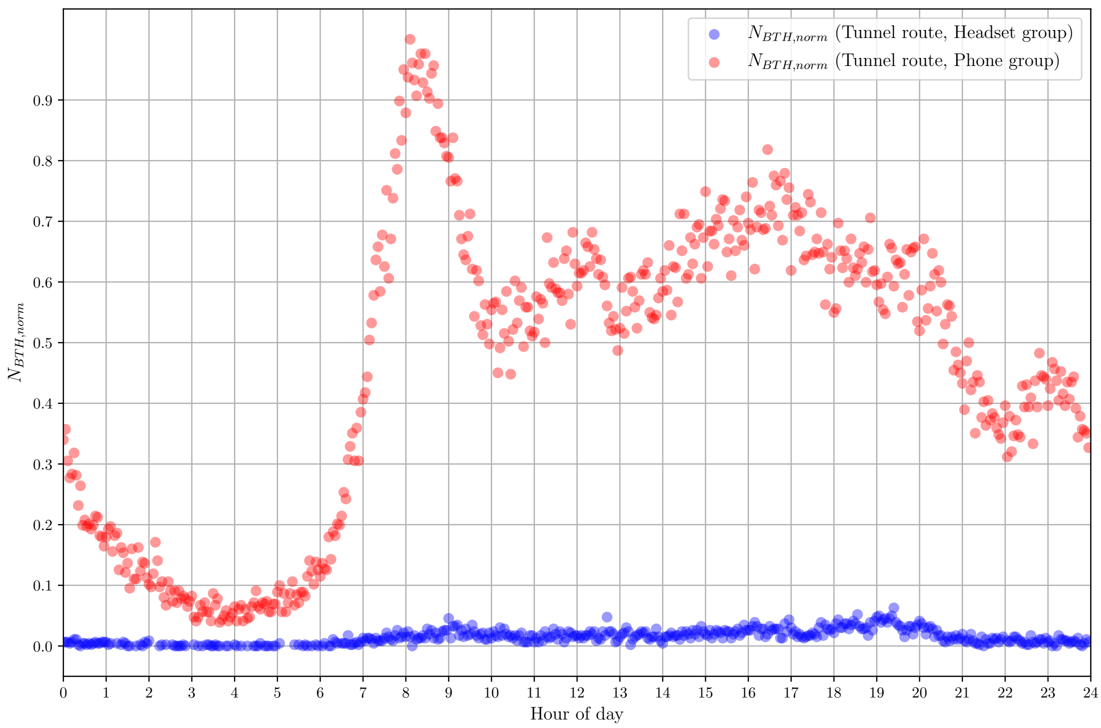

Figure 4.26 – Normalized TT records count on the tunnel route, for the two identified groups of equipments.

distribution of Π given N, i.e. $P(\Pi|N = n)$.

Figure 4.27 plots the conditional distribution $P(\Pi|N = n)$, represented by its 25th, 50th (median) and 75th percentiles, for the phone group (the largest one), over the tunnel and surface routes. The diagram shows two fundamental characteristics of the Champs Elysées to Grande Armée origin-destination:

- The tunnel is, in terms of number of records, the busiest of the two possible routes, with N spanning from 19 to 463. The surface route is far less attractive given the grade-separation provided by the tunnel: N only spans from 16 to 210.
- The origin-destination is subject to little to no congestion, as travel-times remain remarkably stable for the whole range of N, with of course higher travel-times by the surface (median travel-time of 130 s) than through the tunnel (median travel-time of 98 s). More dispersion is observed for the surface route (interquartile range of 53 s, compared to 35 s for the tunnel), subject to traffic lights and fewer records than through the tunnel. Tunnel travel-times see a slight increase for $N \geqslant 250$. For $N \geqslant 350$, few records are available, and greater variability of the percentiles can be seen.

Figure 4.28 plots the conditional distribution $P(\Pi|N = n)$, represented by its 25th, 50th (median) and 75th percentiles, for the headset group, over the tunnel and surface routes. The low number of records is striking, underlining the gap in equipment rate between the first (phones) and the second equipment group (headsets).

Median travel-time (and the 25th percentile) for both routes (surface, 86 s, and tunnel, 85 s) is stable and almost identical. It is coherent with the past assumption made regarding who most likely is behind the headset group: motorized two-wheelers. Their agility and ability to navigate between vehicles and obstacles gives them a very competitive travel-time compared to the majority of traffic (the phone group) through both routes, resulting in a balanced route choice for them. Moreover, contrary to the phone group, the N range for both routes is the same, again confirming that their route choice is not as determined as for general traffic.

One could argue that the tunnel provides a “safer” route as it bypasses at-grade traffic lights and a very busy (and tricky for two-wheelers) roundabout, but the data instead shows a balanced route choice.

The upper travel-time values (75th percentile) nevertheless translates the variability of the surface route travel-time (the interquartile range is 53 s), compared with the tunnel, which offers a somewhat “guaranteed” travel-time centered around its median value (the interquartile range is 36 s).

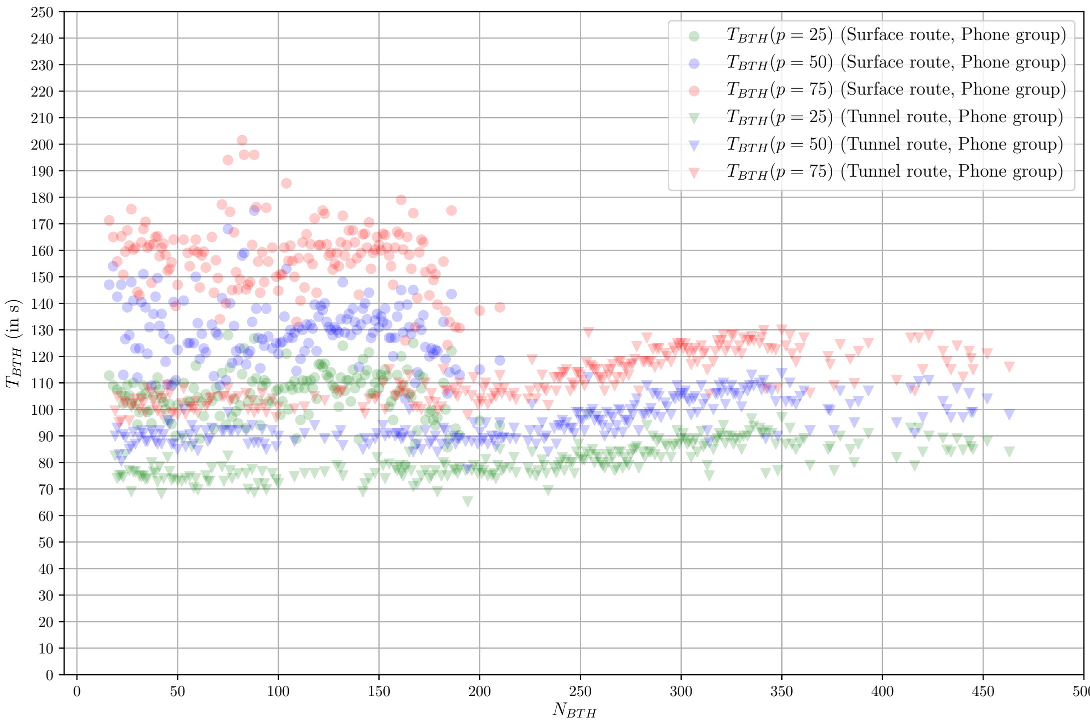

Figure 4.27 – $P(\Pi|N)$, for tunnel and surface routes, Phone group of equipments.

The Champs Elysées to Grande Armée origin-destination, with its two competing routes, either through the surface or the tunnel, allowed to investigate the dynamics of the Bluetooth volume (number of equipments) and of the Bluetooth travel-time, both considered as time series.

The Bluetooth volume remarkably follows the trend traffic loops volume, although some gaps can be observed, especially on the non-free-flow at grade alternative through the traffic circle. No satisfactory explanation could be found for this discrepancy. A plausible assumption would be that during peak hour, vehicles that cannot take the tunnel are not much equipped with Bluetooth-enabled devices.

Moreover, the Bluetooth equipments population can be split into two major categories, thanks to the identifiable equipment types and the resulting travel-time distributions. The “Phone” category, which includes Hands-free devices, Cellular phones, and Smart phones records, can be associated with general traffic, whereas the “Headset” category, which includes Wearable headset devices, seems to mainly represent motorized two-wheelers.

The travel-time time series of the two categories shows that the “Headset” group maintains a more competitive travel-time than the “Phone” group throughout the day. The “phone” group is subject to the rise of travel-times during peak hours, especially for the surface route, the tunnel

Figure 4.28 – $P(\Pi|N)$, for tunnel and surface routes, Headset group of equipments.

route remaining mostly free-flowing all-day long.

Relating the travel-time time-series with the number of record time-series on one scatter plot, which can be called a "Bluetooth fundamental diagram", yields another useful operational tool to assess the influence of equipment volume on travel-times, and compare routes for the same origin-destination.

4.6 After the tunnel's closure: the distribution of Bluetooth travel-times

After the tunnel's closure on March 15th, 2015, some political tensions could be felt on the subject. The main argument was to say the Champs Elysées were clogged up even more than before now that all traffic had to cross the Place de l'Etoile at-grade. The PCE Lutèce had to deliver data on a weekly basis, and still more trust was given into the traditional VKT_{norm} and V_{BRP} indicators taken over the Champs-Elysées and the Grande Armée (sometimes even globally as one same route from Concorde to Porte Maillot, even though the Place de l'Etoile was therefore not included in the computations as it has no traffic sensors) than into the "new" Bluetooth data.

The final report was issued by the author on mid-September 2015, in which traffic loops data of the first half of September 2015 was compared with the similar period in Septembre 2014. Bluetooth data from the first half of September 2015 was compared with the "reference period" from February 1st, 2015 to March 15th, 2015, as no valid Bluetooth data was available for September 2014. All the comparisons were done on business days (Monday to Friday).

In what follows the comparisons will be made over the same business days timeframes for both traffic loops and Bluetooth data : the reference period runs from February 1st to March 15th, 2015, and the post-closure period runs from September 1st to October 15th, 2015.

Group name	Period	Route	Count N_Π	25th p.	50th p.	75th p.	average	st. dev.	IQR
Headset	ANTE	Surface	3,521	66	86	119	100	114	53
Headset	ANTE	Tunnel	3,577	68	85	104	87	26	36
Headset	POST	Surface	7,262	124	158	195	170	69	71
Phone	ANTE	Surface	50,948	106	130	159	143	183	53
Phone	ANTE	Tunnel	103,454	82	98	117	101	55	35
Phone	POST	Surface	131,683	153	192	259	213	86	106

Table 4.2 – Champs Elysées to Grande Armée origin-destination. Descriptive statistics by group (Headset or Phone) and period (Ante or Post) and route (Tunnel or Surface) of the Bluetooth travel-times.

The analysis of Bluetooth travel-time, to answer the operational questions, follows the guidelines previously hinted in observing the various aspects of the dataset. As previously stated, only records that are either part of the Phone or Headset categories are kept.

For each of the two groups of equipments, the travel-time distributions of two origin-destination pairs are considered:

- the Champs Elysées to Grande Armée origin-destination (surface and tunnel routes);
- the Grande Armée to Friedland origin-destination.

The analysis of the two routes follows the guidelines hinted in the previous sections.

4.6.1 The Champs Elysées to Grande Armée origin-destination

The comparison of travel-times for the Champs Elysées to Grande Armée origin-destination, over the tunnel and surface routes, is the key result that was expected from the program.

A first level of analysis of the travel-times is provided by the aggregate statistics (Table 4.2) over each group, period and route. The surface median travel-time, for both categories of equipments, increases: it doubles for the Headset group, and increases by nearly 50 % for the Phone group. In both cases, the surface travel-time after the closure is double that of the tunnel. The associated spread indicator, the IQR, shows an increase in the variability of the travel-times: the IQR for the surface route increases by 50 % for the Headset group, and doubles for the Phone group. The tunnel IQR is doubled for the Headset group, and tripled for the Phone group.

The mean travel-time also increases in the same proportions as the median, nonetheless, its associated spread indicator, the standard-deviation, shows a decrease for the surface route between the two periods (but an increase between the tunnel before the closure and the surface route after the closure).

These observations are confirmed by the distributions, plotted Figure 4.29 for the Phone group and Figure 4.30 for the Headset group.

In both cases the Tunnel route showed a little dispersed distribution, with a very limited tail. Before the closure, the surface route showed two distributions: for the Phone group, an important dispersion, whereas the Headset group kept a distribution close to the tunnel's. After the closure, the surface distribution of both routes are shifted towards upper values, although the Phone group offers a higher dispersion than the Headset group.

The Champs Elysées–Grande Armée median travel-time time series, computed t_{03min} slots for each group, period and route, and plotted on Figure 4.31, shows the time dependency of the different travel-time distributions, and confirm the analysis carried out on the distributions.

Before the tunnel's closure, the median travel-time generally remains between 1 and 2 min for all categories of equipments and routes. For the Phone group, the surface and tunnel median travel-times are only on average separated by 30 s. The only major difference in trend is the evening peak, between 18:00 and 20:00, during which the tunnel median travel-time remains stable whereas the surface median travel-time increases by nearly a minute. For the Headset (assumption made they are motorized two-wheelers) group, the median travel-time is much more scattered, but still overall bounded between 1 and 2 min, in the vicinity of the tunnel's median travel-time. The scatter is explained by the low population, but is also compatible with the two-wheeler assumption: given their tendency to zigzag between cars, they surely drive faster than them but can get stuck from time to time, hence the dispersion of the median.

After the tunnel's closure, the surface route becoming the only option, the situation is radically different, especially from 07:00 to 21:00. For the Phone group, the threshold travel-time for the period is 3 min (from 2 min on the same route when the tunnel was opened), and three peaks in travel-time can be identified:

- the morning peak, from 07:00 to 10:00, the median travel-time peaking at 08:30 at nearly 4 min (from 2 min on the same route when the tunnel was opened);
- the noon peak, from 11:00 to 13:30, the median travel-time peaking around 12:30 over 4 min (from 2 min on the same route when the tunnel was opened);
- the evening peak, which starts at 14:00, a travel-time threashold being kept around 4 min 30 s until 18:00, when it increases to peak at 6 min (from 3 min on the same route when the tunnel was opened) at 19:00.

For the Headset group, these dynamics can also be observed, although the dispersion of their travel-times is higher, and they generally stay in a range of travel-times between 2 and 4 min, but double their ante travel-time.

These travel-time variations translate a congested state of the intersection after the tunnel's closure, with travel-times "responding to the traffic demand": as the traffic volume increases, there is quickly no spare capacity left, and the traffic state evolves towards a more congested state.

The distribution Π_{DELAY} of the delay inflicted by the tunnel's closure on the travel-time distribution between the Champs Elysées and Grande Armée can be seen as the difference:

$$\Pi_{ANTE} + \Pi_{DELAY} = \Pi_{POST} \tag{4.6.1}$$

where Π_{ANTE} is the travel-time distribution for the origin-destination, including both tunnel and surface routes, before the tunnel's closure, and Π_{POST} the travel-time distribution for the origin-destination for the surface, the sole remaining route after the tunnel's closure.

Figure 4.32 shows the hourly time lost on the origin-destination. For each period (ANTE and POST), the spent time T_L on the origin-destination is the sum of each value of Π weighted by its number occurrences $N(\Pi)$. The time lost is highest at night between 01:00 and 03:00, and is then spread during the day, with the morning peak (08:00 to 10:00) and then the late afternoon and evening peak period (15:00 to 20:00).

One could argue that the Bluetooth data only covers a portion of the total traffic flow, and that therefore if the Bluetooth yields a proper estimate of travel-times, the time lost should have been computed by weighing the travel-times by the traffic loops counts, and not the Bluetooth counts. Several points support the use of Bluetooth counts:

- Faulty sensors mean some of the volume data measured is suspicious;
- Sensors only measure volumes at a given point, but are not origin-destination specific, unlike Bluetooth sensors;
- If the fact that Bluetooth travel-time are held as reasonable estimates of travel-time, why

consider the associated volumes as not relevant?

- The resulting time lost will be Bluetooth-relative.

Of course the time lost is computed for the traffic volume that still uses this route and has not completely changed its routing strategy (i.e., completely avoid the Place de l'Etoile area). Further analysis on nearby traffic loops showed that favored bypass used the riverbank expressway to the South of the plaza, where some residual capacity was available.

The Champs Elysées to Grande Armée origin-destination suffers from the closure of the tunnel, with worsening traffic conditions. Nonetheless, not all categories of equipements are impeded in the same proportion. The Phone group sees a more than doubling median travel-time with increased variability, whereas the Headset group, although impeded, is able to keep a more competitive travel-time.

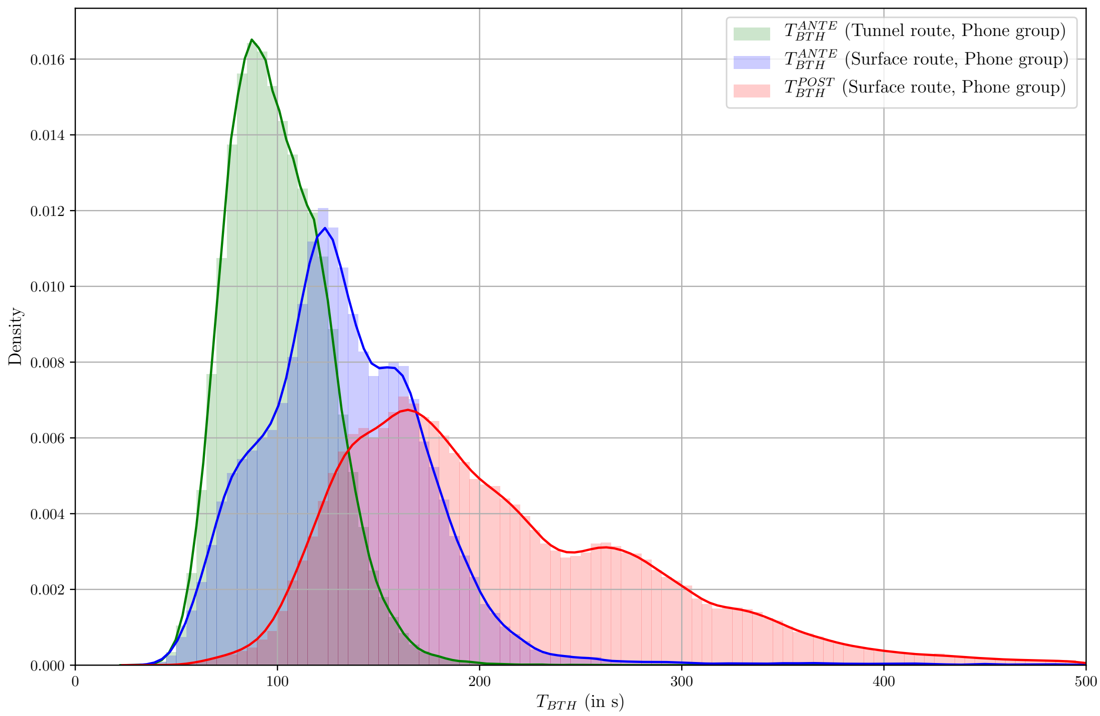

Figure 4.29 – Champs Elysées to Grande Armée origin-destination. Travel-time distributions for Phone group of equipment, for ANTE (Surface and Tunnel) and POST (Surface only) periods.

4.6.2 The Grande Armée to Friedland origin-destination

Only one route, through the traffic circle, allows the Grande Armée to Friedland origin-destination.

The flow of traffic from Grande Armée to Friedland, accounts for 20 % of records of the Bluetooth-monitored origin-destinations originating from Grande Armée, namely Grande Armée to Champs Elysées and Grande Armée to Friedland. The impact of the tunnel's closure on this turning movement was feared by the Préfecture de Police, who expected the additional traffic flowing on the circle from the Champs Elysées to block the conflicting movement and hence initiate a complete gridlock of the intersection.

The method adopted follows the same line as the Champs Elysées to Grande Armée origin-destination, with considering the two categories, or groups, of equipments, namely the Phone

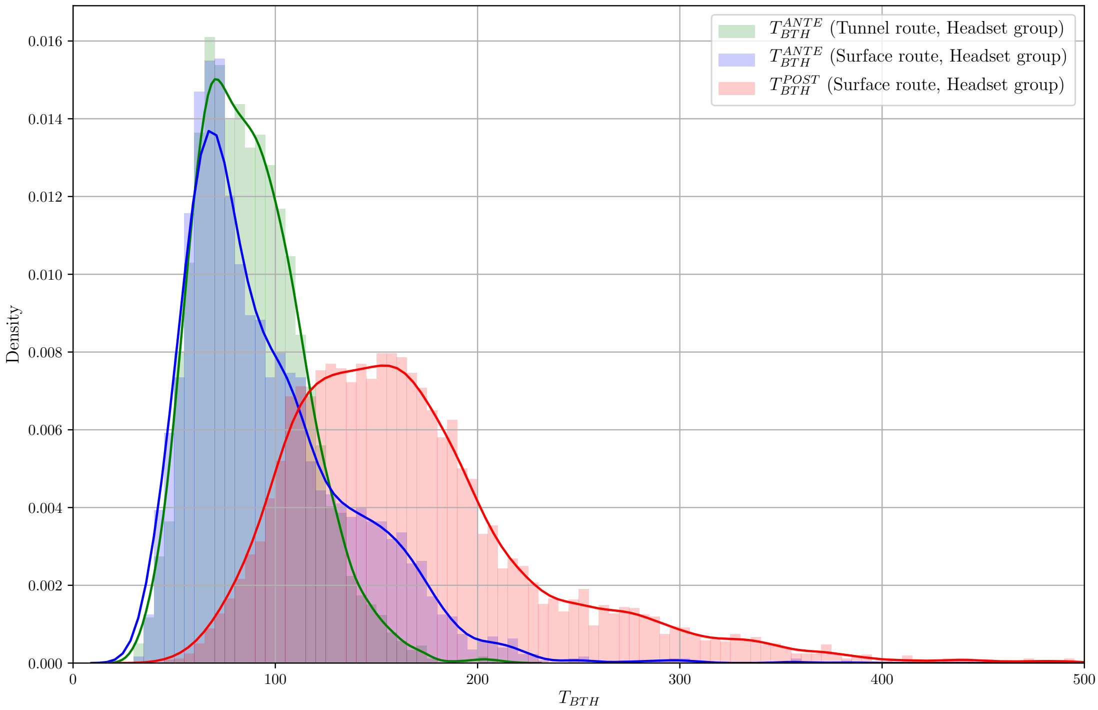

Figure 4.30 – Champs Elysées to Grande Armée origin-destination. Travel-time distributions for Headset group of equipment, for ANTE (Surface and Tunnel) and POST (Surface only) periods.

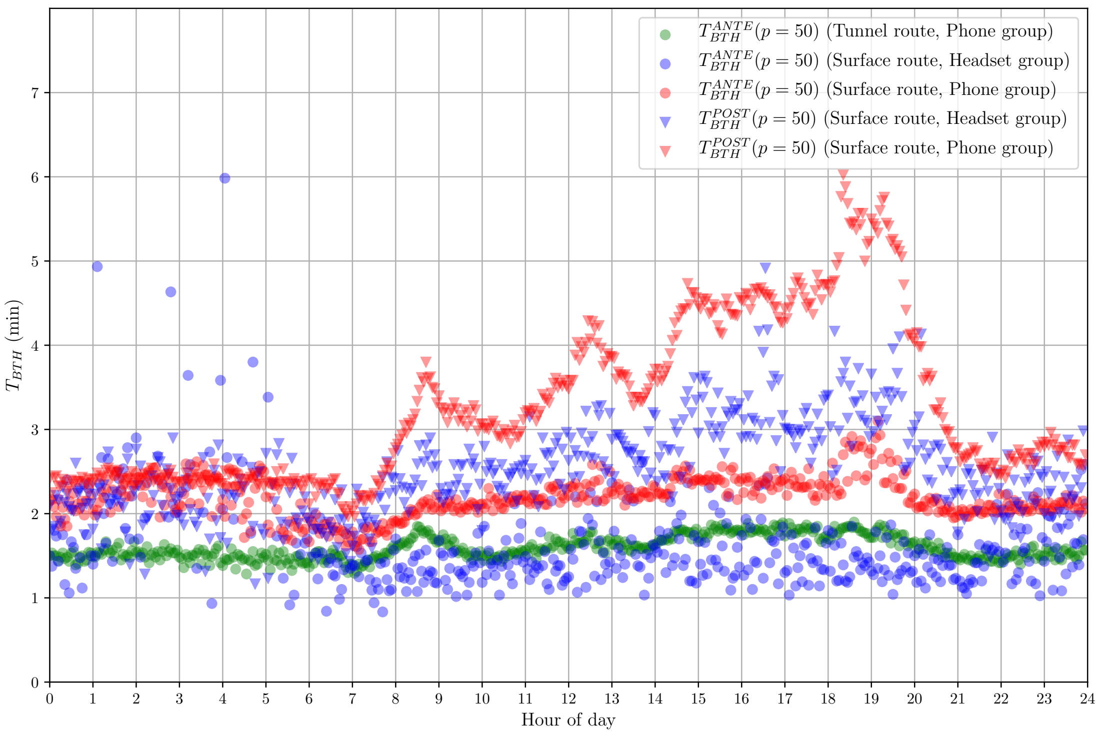

Figure 4.31 – Champs Elysées to Grande Armée origin-destination. Median travel-time time series (computed per t_{03min} slots for ANTE and POST periods, and per group).

group and the Headset group. The Headset group is assumed to mostly consist of motorized two-wheelers.

Table 4.3 gives the aggregate statistics before and after the tunnel's closure, for both groups.

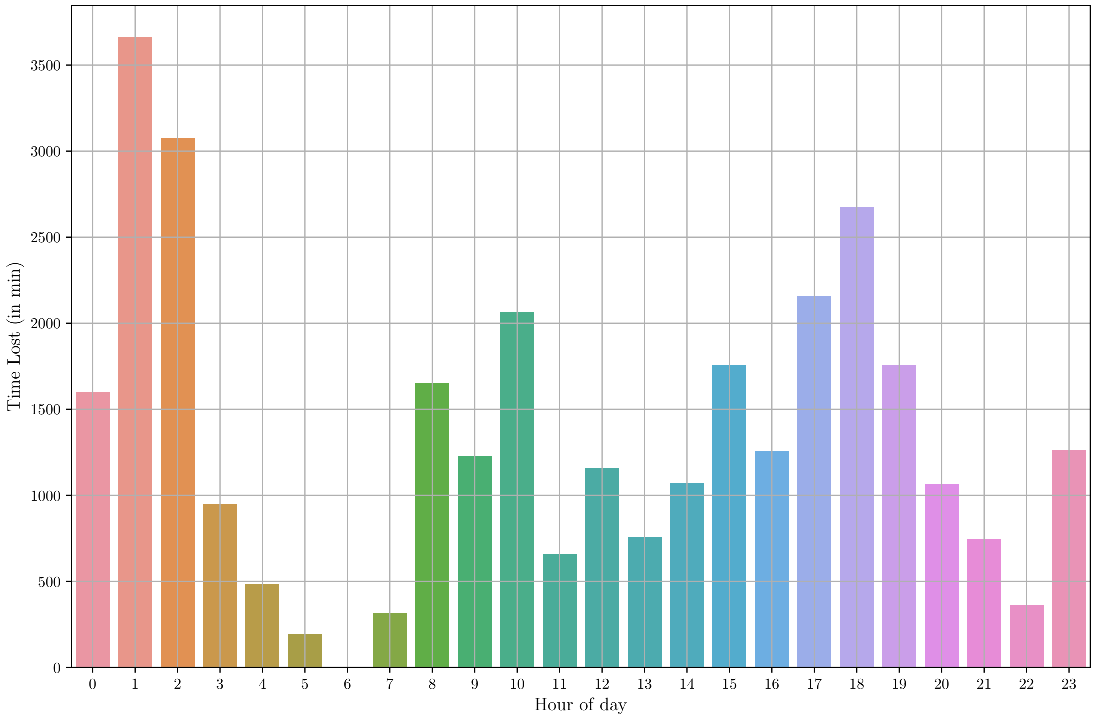

Figure 4.32 – Travel-time histogram for Headset group of equipment of the difference Π_{DELAY}.

The median travel-time of both groups increases in the same proportion, of about 20 s, from 103 s to 117 s for the Headset group, and from 132 s to 152 s for the Phone group. The variability of the travel-time also increases: the IQR increases more for the Phone group. The average travel-time of both groups is also increased, this by 30 to 40 s, along with an important increase of the standard deviation: from a 128 s to 152 s average with a standard deviation from 215 s to 270 s, for the Headset group, and from a 193 s to 239 s average with a standard deviation from 401 s to 483 s for the Phone group. The tunnel's closure clearly has a non-negligible impact on the Grande Armée to Friedland turning movement.

The distribution of the travel-times is shown by Figure 4.33 for the Phone group and Figure 4.34 for the Headset group.

The Phone distribution shows two modes, with the first mode dominating the second. After the tunnel's closure, the distribution is shifted towards higher travel-times, the first mode being reduced in favor of the second mode and a longer tail.

The Headset distribution is unimodal with a tail into higher travel-time values, and stays as such after the tunnel's closure, although also shifter towards higer travel-times, with a lower mode and a more important tail.

In both cases, this shows the impact of the tunnel's closure on both the central tendency of the travel-times, but also their variability.

The median travel-time series (Figure 4.35) shows the time dynamics of the distributions. The values are generally very scattered at night, between 00:00 and 05:00; this is mainly explained by the low population during this period.

During the day, before and after the tunnel's closure, the Phone group median travel-time follows the same trend. The threshold value simply jumps from the 2 min to 2 min 30 s interval to the 2 min 30 s to 3 min interval. This threshold value is marked by two major peaks, which worsen with the tunnel's closure:

Group name	Period	Count N_{Π}	25th p.	50th p.	75th p.	average	st. dev.	IQR
Headset	ANTE	1,978	81	103	127	128	215	46
Headset	POST	2,697	92	117	145	152	270	53
Phone	ANTE	37,697	112	132	176	193	401	64
Phone	POST	38,527	121	152	215	239	483	94

Table 4.3 – Grande Armée to Friedland origin-destination. Descriptive statistics by group (Headset or Phone) and period (Ante or Post) and route (Tunnel or Surface) of the Bluetooth travel-times over the Grande Armée to Friedland origin-destination.

- in the morning (from 08:00 to 10:00, with a peak at 09:00), with a peak from 3 min 30 s to 4 min 30 s;
- in the evening (from 18:00 to 20:00, with a peak at 19:00), with a peak from 3 min to nearly 5 min.

The Headset group follows the same trend as the Phone group, with morning and evening peaks of its median travel-time, but generally around 1 min lower than the Phone group, and with greater dispersion of the median values. This dispersion, like for the Champs Elysées to Grande Armée case, can be explained by two factors: the driving habits of two-wheelers, and the low population.

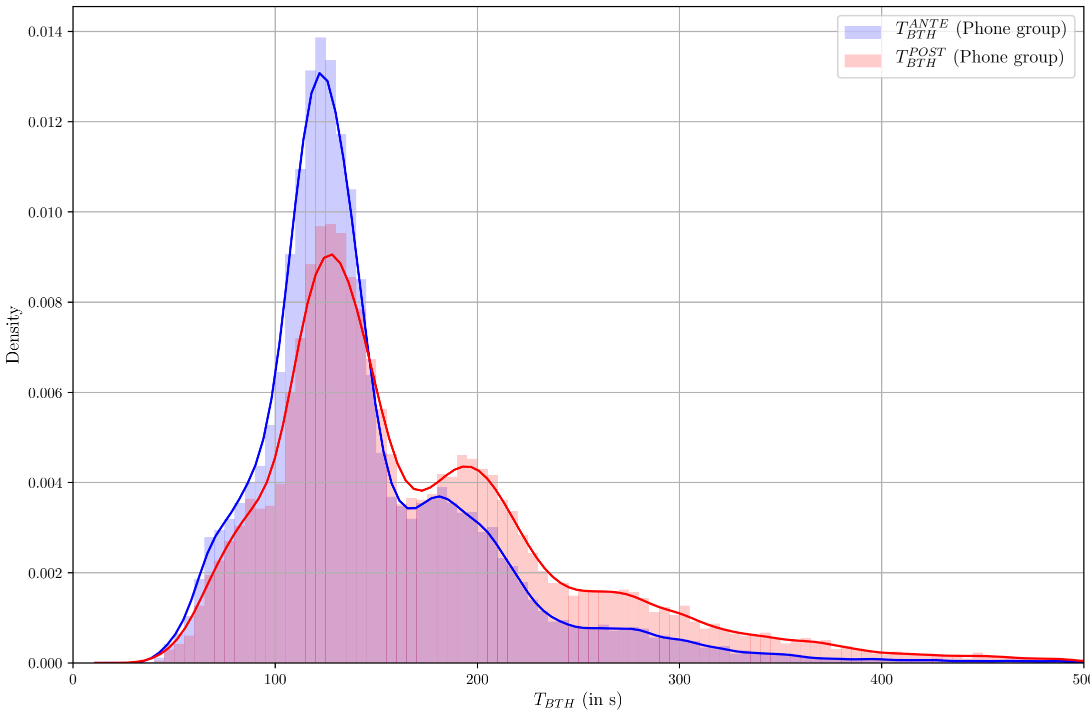

Figure 4.33 – Grande Armée to Friedland origin-destination. Travel-time distributions for Phone group of equipment, for ANTE and POST periods.

The study of the Bluetooth travel-time distributions over the two origin-destination that raised concerns yields key figures allowing to quantify the consequences of the closure of the tunnel.

The study guideline is each time straightforward and involves statistics of a limited complexity.

As observed during the investigations carried over the Bluetooth dataset, the population of

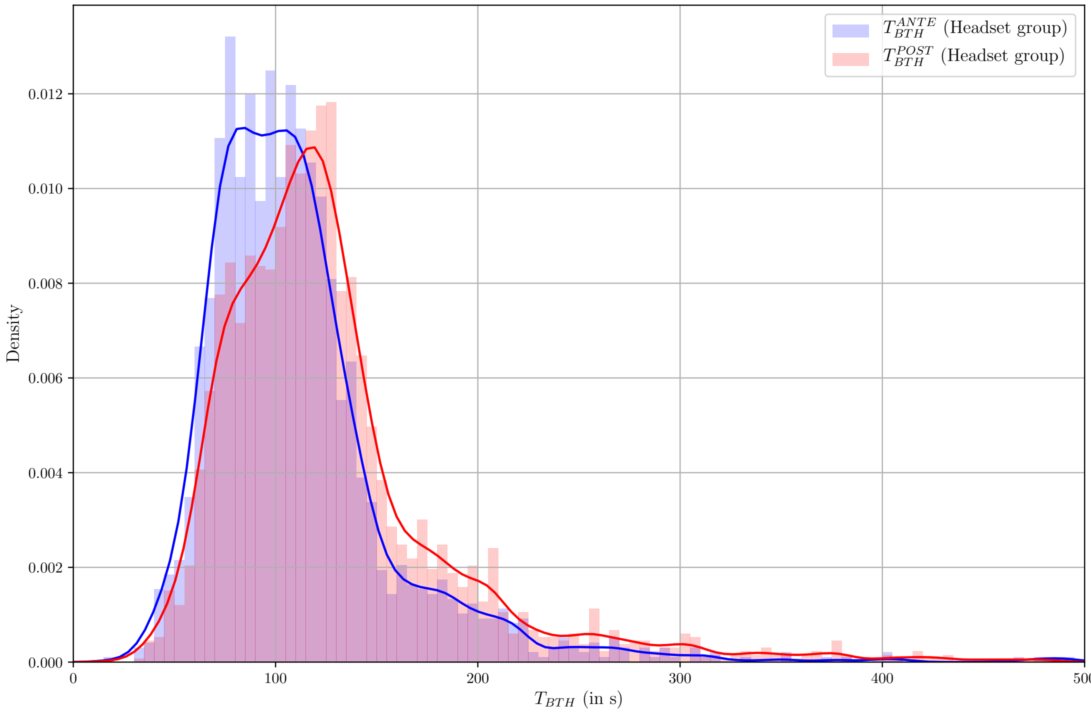

Figure 4.34 – Grande Armée to Friedland origin-destination. Travel-time distributions for Headset group of equipment, for ANTE and POST periods.

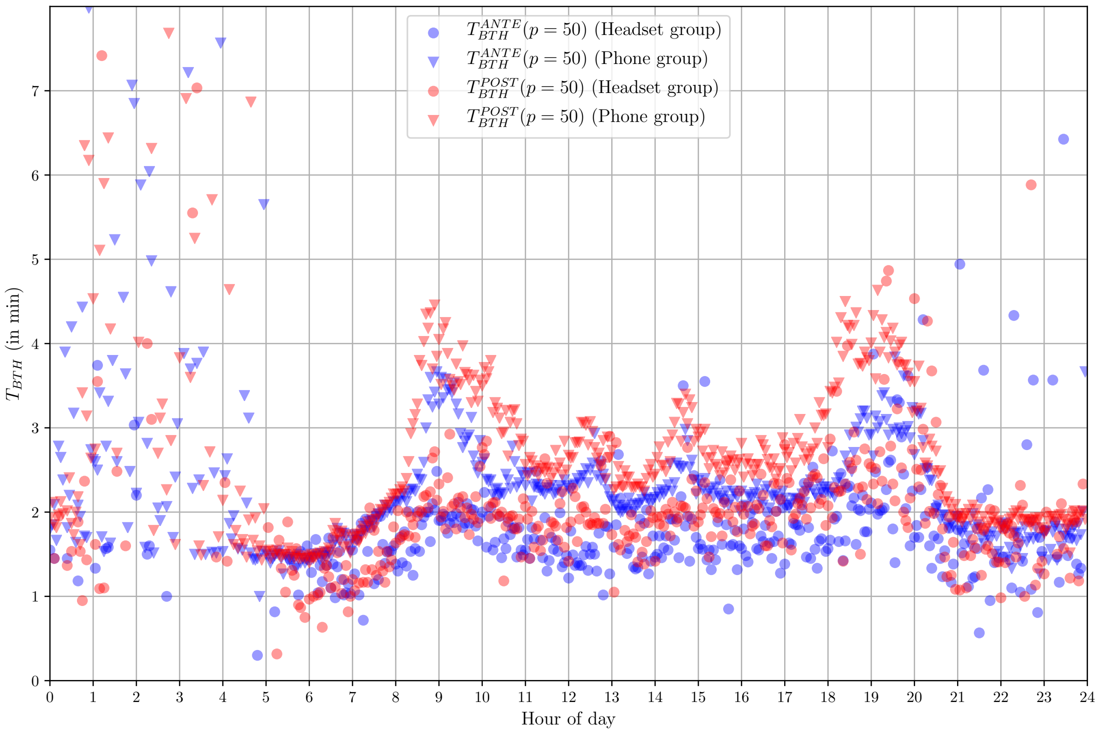

Figure 4.35 – Grande Armée to Friedland origin-destination. Median travel-time time series (computed per t_{03min} slots for ANTE and POST periods, for Phone group).

equipments can be usefully split into two categories, namely Phone and Headset. Evidence of the travel-time distributions serve the reasonable assumption that the Phone groups accounts for equipments traveling aboard standard vehicles, whereas the Headset group is onboard the motorized two-wheeler fleet.

With these two groups, the first step of the study involves binning the data by period of comparison, groups of equipments and route, as each origin-destination pair may have several routes. The aggregated statistics along with the empirical distribution of the travel-times for each bin yield figures on the traffic conditions as seen through the Bluetooth equipments.

The second step clears the time dependency of the distributions, by studying how median travel-time values evolve through time. The median time series, computed over small time slots (the same as the traffic sensors data: t_{03min}), shows the dynamic of traffic throughout the day.

The first origin-destination studied, from the Champs Elysées to Grande Armée, is clearly impeded by the closure of the tunnel, that affects the two groups of equipments. Both the central tendency of the travel-times (median and average) and their variability increase, translating a more congested state of traffic with the higher unreliability of travel-times for the users.

The second origin-destination, the turning movement onto Friedland for equipments coming from Grande Armée, is also impeded by the additional input of traffic coming from the Champs Elysées, with a limited increase of the travel-times but an increased variability.

The tunnel's closure not only has increased the travel-time of vehicles traversing it: it has decreased its reliability, and created additional congestion on a location that used be less prone to it.

4.7 Conclusion

The Place de l'Etoile stands as a major interchange of Paris road network. The Grande Armée and Champs-Elysées axis constitutes the major route across the plaza both for Eastbound and Westbound traffic, and underlines the key role played by the tunnel in allowing free-flowing Westbound movement from the Champs to the Grande Armée.

Assessing the impact of its closure on both the Champs Elysées to Grande Armée and the Grande Armée to Friedland origin-destinations could not be carried out by traditional means. Traffic sensors only provide indicators over the arterials themselves, but not on the plaza, where no sensors are implemented. Moreover, the general derelict state of the sensors, with high unavailability rate, rendered them of little use.

The assessment therefore relied on travel-time indicators derived from Bluetooth equipment detections. The Bluetooth travel-time relies on the timestamped detection of the MAC address of Bluetooth-enabled equipments that pass within the detection range of dedicated beacons scanning the Bluetooth frequencies. For an origin-destination pair between a beacon B_1 and a beacon B_2, this yields a table of travel-time records. Each travel-time Π is associated to an anonymized MAC address a, an equipment type e and the reference timestamps t_1 and t_2 selected for each of the two beacons.

Installing the beacons ended up being complex operation, involving several stakeholders, which the author had to coordinate. The field forced a modification of the original setup due to unforeseeable interferences and side effects.

The population of Bluetooth-enabled equipments detected can be split into two major categories, thanks to the identifiable equipment types (from the MAC addresses) and the resulting travel-time distributions. The "Phone" category, which includes Hands-free devices, Cellular phones, and Smart phones records, can be associated with standard vehicles, whereas the "Headset" category, which includes Wearable headset devices, seems to mainly represent motorized two-wheelers.

The evolution through time of the Bluetooth volume (number of detected equipments per time unit) generally remarkably follows the trend traffic loops volume, although some discrepancies could be observed.

The travel-time from the Bluetooth equipment perspective is more a user-based perspective than a traffic flow one, as provided by the legacy traffic loops. Each equipment is either attached to a user or to a vehicle. Moreover, not all vehicles or users are equipped with Bluetooth-enabled equipment, the population of which only samples the whole flow. This, for a part, can explain the observed discrepancies between the traffic loops and Bluetooth equipment volumes.

The study of the Bluetooth travel-time distributions over the two origin-destination pairs that raised operational concerns yielded key figures allowing to quantify the consequences of the closure of the tunnel.

The study guideline of these travel-time distributions is each time straightforward and involves statistics of a limited complexity.

With the two Phone and Headset groups, the first step of the study involves binning the data by period of comparison, groups of equipments and route, as each origin-destination pair may have several routes. The aggregated statistics along with the empirical distribution of the travel-times for each bin yield figures on the traffic conditions as seen through the Bluetooth equipments.

The second step clears the time dependency of the distributions, by studying how median travel-time values evolve through time. The median time series, computed over small time slots (the same as the traffic sensors data: t_{03min}), shows the dynamic of traffic throughout the day.

The first origin-destination studied, from the Champs Elysées to Grande Armée, is clearly impeded by the closure of the tunnel, that affects the two groups of equipments. Both the central tendency of the travel-times (median and average) and their variability increase, translating a more congested state of traffic along with a higher unreliability of travel-times for the users.

The second origin-destination, the turning movement onto Friedland for equipments coming from Grande Armée, is also impeded by the additional input of traffic coming from the Champs Elysées, with a limited increase of the travel-times but an increased variability.

The tunnel's closure not only has increased the travel-time of vehicles traversing it: it has decreased its reliability, and created additional congestion on a location that used to be less prone to it.

In the end, the Bluetooth travel-time experiment of the Place de l'Etoile offered a user-perspective of its traffic conditions in terms of time, which could not have been approached by the legacy traffic loops.

Chapter 5

Voie Express Rive Droite: Bluetooth beacons for a major road closure

5.1 Introduction

The Right Bank Expressway, or "Voie Express Rive Droite", was the main arterial road, mostly grade-separated, allowing free-flowing movement from West to East across Paris and its central core, following the Seine River. Built in the 1960s to allow easy access to Paris central districts and reduce its dreadful daily jams, it came, with the turn of the century, under increasing political scrutiny, as one of the symbols of the pollution and congestion woes associated to motor traffic. The 2014-elected City of Paris Administration, in line with their political projects, decided to close the expressway in central Paris by Summer 2016.

Meanwhile, the successful experiment of the Bluetooth beacons at Place de l'Etoile, lead the PCE Lutèce and the Author to devise a Bluetooth-based assessment of the forthcoming closure, by reusing the four beacons on the two corridors directly impacted by the expressway closure: these would act as the main diversion routes. The Bluetooth would allow to get a user-perspective indicators that the legacy loop-based methods failed to provide.

The original operational needs stood as such:

- How much time does a journey across central Paris takes with the expressway?
- With the expressway closed, how much time does a journey across central Paris now takes over the two main diversion routes?
- Additionally, how would traffic conditions evolve on the two main feeding routes coming from the West, and on the main outbound route to the East?

The two first operational needs could be answered by the four original Etoile beacons, but additional funding had to be made available for the third point, in order to acquire additional beacons.

The Bluetooth equipments allowed to collect travel-time values for a few months before the closure, and then follow both how the situation was compared to before, and how it evolved through time as motorists adapted their behavior to the new situation. For the inbound and outbound routes monitoring, this could only be carried out after the closure, due to the delay in funding and installation of the beacons.

Besides these operational grounds, the experiment allowed a more in-depth evaluation of the Bluetooth travel-time, this time on whole several kilometer-long corridors, compared with traditional sensor-based methods, and not only on restricted locations like on Place de l'Etoile.

This Chapter first presents the historical, functional and political context of the Right Bank Expressway, and the different phases of beacons deployment as additional funding was made available. Then, it shows how Bluetooth travel-time, whose main characteristics have already been described in the Place de l'Etoile chapter, can be operationally used to discriminate route choices both through space (which physical route is taken by the Bluetooth equipment) and time (based on the time of day/traffic conditions, which route is chosen by the Bluetooth equipment's holder). They also allow to introduce some more theoretical aspects of traffic engineering, with the interval between detections and the free-flow speed issues. Finally, the Chapter closes on some of the operational conclusions derived from the measured travel-times.

5.2 Context

The Seine riverbanks have indeed acted as a major arterial serving the city center even before the expressway, and then during the nearly fifty years of operation of the road.

This section presents the historical, functional and political context of the Right Bank Expressway, from its inception, then its operation, and finally its closure in Summer 2016. It then shows the operational context of the progressive deployment of Bluetooth beacons as the studied perimeter was extended to Paris limits.

A map, Figure 5.1, presents the Bluetooth-monitored routes and associated ADT computed before the expressway's closure.

5.2.1 The Seine riverbanks as a major arterial

The Seine River flows across Paris from East to West. Starting in the XVIth century, its shores have progressively been banked up with masonry walls. Built up areas along the river were gradually reconstructed on embankments several meters above the water, with boulevards running between the buildings river alignment and the embankment wall, topped by a parapet, bordering the River itself. A passage, used as a towpath and harbor, remained at the water's level. Work on these embankments was massively carried out in the XIXth century, along with bridges enlargements and reconstructions to ease navigation. This yielded the current layout of the Seine River in Paris.

The former towpaths are known as the "Quais Bas", or Lower Bank, whereas the boulevards, on the embankments, are known as the "Quais Hauts", or Upper Bank.

With the rise of motor traffic from early XXth century onward, already in the 1930s, congestion quickly became an issue on the Quais Hauts, with the then at-grade junctions at major bridge heads becoming gridlocks. In the 1950s, some of them were grade-separated by underpasses, easing the free-flowing movement of the Quais Hauts.

In the 1960s, the towpaths appeared as a convenient base to build a crosstown expressway at limited cost, connecting the already built underpasses, and ultimately offering a free-flow connection between the central core of the city, the ringway and the Paris region's expressway network. Running along the Seine meant that little to no land would have to be vested, very few buildings would have to be demolished in one of the densest European cities, and grade-separation would "naturally" come from the river bridges: the expressway, running near the water level, would be going underneath them. At points were the towpaths were too narrow, space would be gained over the river or tunnels would be built, as was done along the Louvre.

The completed Right Bank expressway was inaugurated on December 22, 1967 by Georges Pompidou, the Prime Minister of President De Gaulle. Its central section, between Concorde and Mazas, included a 800 m tunnel, the Tunnel des Tuileries, along the Louvre.

It is now known either as the "Voie Georges Pompidou" (literally Georges Pompidou Way, abbreviated VGP) or *Voie Express Rive Droite* (Right Bank Expressway), its original name.

The expressway itself is a one-way grade separated two-lane road, running from West to East, allowing free-flow traffic movement between West Paris (Point du Jour), Central Paris (Châtelet) and East Paris (Bercy) where it directly plugs into the Eastbound A4 motorway, the major artery linking Paris to its eastern suburbs, and beyond to Germany via Strasbourg.

Its counterpart, which would have allowed free-flow movement from East to West along the left bank of the river, was only partially built in the 1960s. Its final central section was axed in 1974 amid growing concerns on its feasibility and the damage it would have done to Paris historical core (place St Michel, Notre Dame), especially with the Right bank expressway being already opened and criticized.

5.2.2 Closing the expressway

The central section of the expressway, between Concorde and Mazas, remained the most controversial.

It was periodically closed to motorized traffic starting in 1995, on Sundays, and the roadway could then be used by pedestrians and cyclists as a promenade.

After the 2001 municipal election, a periodic Summer closure, lasting several weeks, when the traffic levels are at their lowest, was instated. The operation was first known as "Paris-Plage", then "Paris-Plages" (Paris Beaches), during which the expressway (except for the Tuileries tunnel) was turned into a beach with sand, parasols, etc.

In 2012, traffic lights were installed on the corridor, mainly on the central section, in order to turn the expressway into a "boulevard". This operation was followed by the closure in March 2013 of the sole constructed section of the Left Bank expressway, subsequently turned into a promenade.

In 2014, the newly elected Mayor of Paris, Anne Hidalgo, campaigned on the total closure of the expressway's central section. It was subsequently closed, as usual since 2002, on July 13th 2016 to give way for Paris Plages, but did not reopen to traffic once the latter event was over.

The Conseil de Paris voted the closure on September 26th, 2016: the debates were concluded by the Mayor as "a historical decision: the end of an urban expressway and the reconquest of the Seine" ([110])[1]. The West and East part of the expressway, respectively feeding the central section and leaving the central section, were kept operational. Nonetheless, operations to reduce the capacity from two to one lane to the West part were carried out by phases, from 2016 to 2017. The canceled lane was turned into a bus lane and cycling path.

The decision caused much political turmoil, especially from the West, as politicians and citizens were worried about the congestion they would suffer from the break of continuity of the expressway and the capacity reduction, to one lane, of the West segment. The Préfecture de Police also expressed concerns on the traffic conditions in central Paris following the closure of the expressway.

A one-year Commission was set up, under the authority of the Greater Paris administrative body and including several municipalities, neighboring Départements, transit agencies and operators. Its role was to follow the consequences of the closure said to be "experimental" for the first six-month period. The Commission, namely the "Observatoire métropolitain d'expérimentation

[1] "Une décision historique : la fin d'une autoroute urbaine à Paris et la reconquête de la Seine"

de la piétonisation des voies sur berges rive droite", "Metropolitan observatory for the experimental pedestrianization of the Right bank expressway", first gathered on October 7th, 2016, and then on a regular basis until the Summer 2017. After much debate, the closure was made final in June 2017.

5.2.3 A progressively widened Bluetooth deployment program to assess travel-times

By late 2015, the successful experimentation at Etoile was drawing to an end. At the same time, it was becoming clear that the central section of right bank expressway would be closed in Summer 2016. This was seen by the Author as an opportunity to pursue testing of the Bluetooth beacons, this time on a much broader scale since the four beacons were going to be deployed three kilometers apart, at each end of the about-to-be-closed section of expressway.

Moreover, the traffic loops were mostly out of order on the expressway (as it was due to close to no investments being made to restore the loops) and on the Quais Hauts (roadwork, with a long trench along the Louvre that broke down all loops on nearly a kilometer of the corridor). Therefore, on the Right Bank, traditional VKT_{norm} and V_{BRP} indicators could not be computed.

Additional funding was made available during the first half of 2016, which allowed to extend the monitored corridors with five additional beacons.

The Bluetooth sensors setup therefore went through in three deployment phases, from early to late 2016:

a first phase which included four beacons in the city center, around the expressway's central section and its two main diversion routes, the Quais Hauts Rive Droite and the Boulevard Saint Germain;

a second phase which included one beacon at Châtelet, meant to discriminate traffic between the expressway and the Quais Hauts Rive Droite diversion routes. This sensor ultimately failed;

a third phase which included four additional beacons, in order to monitor the main routes leading to the central section of expressway from the West (Porte Maillot, Porte de St Cloud, Quai St Exupéry), and the main outbound route at the end of the central expressway section (Porte de Bercy).

5.2.3.1 The first deployment phase

This first phase of deployment was aimed at assessing the travel-times of two origin-destination pairs crossing the city center from West to East, following the expressway route.

The first origin-destination pair monitored, from beacon Concorde to beacon Sully, includes the Quais Hauts Rive Droite (QHRD) and the expressway (VGP) routes.

The Quais Hauts Rive Droite are a signalized arterial running along the Seine, which has a dedicated bus lane for most of its length, plus two to four lanes of general traffic. Each bridge head it crosses is often a major intersection.

The expressway itself is entirely grade-separated and almost free-flowing, setting aside the three sets of traffic lights added in 2012. Running just a few meters above the river, the roadway skirted all the at-grade intersections by passing under the Seine bridges, except at two locations where it ran into a tunnel, first along the Louvre (Tuileries tunnel), and then along the Quai Henri IV (Henri IV tunnel). Two exit ramps and one entrance ramps, all three located between the two tunnels, allowed exchanges with the Quais Hauts Rive Droite and intersecting streets.

Each beacon was positioned so that it would detect equipments traveling either on the expressway or on the Quais Hauts. The West one, at Concorde, was installed on the the Quai des Tuileries, alongside Tuileries garden, where the expressway and the Quais Hauts (each being a two-lane one-way roadway) ran parallel and at the same level. The East beacon, at Sully, was installed on the Quais Hauts (Quai Henri IV), overlooking the expressway just before it dived inside the Henri IV tunnel, thus detecting equipments of both routes. Traffic passing by the Sully beacon, apart from very local traffic, necessarily joins the expressway a few hundred meters downstream.

Thus, for the Concorde to Sully pair, two distinct routes were possible: either through expressway, or through the Quais Hauts. Combining both routes thanks to the exit and entrance ramps was possible, but remains a rare case scenario.

The second origin-destination pair, from beacon Assemblée to beacon Jussieu, followed the boulevard Saint-Germain, on the Left bank, a major 3.3 km West-East one-way signalized arterial. It has a dedicated bus lane all way long, plus two to four unmarked lanes of general traffic. The pair of beacons allowed to detect equipments traveling the whole length of the boulevard.

The setup went smoothly on January 22nd, 2016, and data was made available starting on February 1st, 2016.

5.2.3.2 The second deployment phase

The fifth beacon was intended to discriminate the two Right Bank routes: the expressway and the Quais Hauts.

The beacon was installed in March 2016.

Unfortunately, it never worked properly: the beacon kept loosing the GSM network, making it impossible to retrieve the collected data. It was first thought that for some reason the beacon was faulty, and it was replaced with a new one, which was intensively tested at the providers' premises. Once on-site, the same connectivity issue arose. The firmware seemed to be out of cause as the same version was already installed on the other beacons and was running very smoothly. All these investigations lasted for several weeks.

The situation encountered at this specific location was never completely cleared out. It was even more surprising that being in the very heart of Paris, the GSM network coverage should have been excellent, and from a personal mobile phone's perspective, it was indeed very good.

In the end, this location was dropped and the beacon removed.

It nevertheless raised an important point, added in the installation procedure: on-site connectivity tests were systematically to be carried out with a spare beacon, during preparatory studies for future Bluetooth beacons deployments.

5.2.3.3 The third deployment phase: four additional beacons for indbound and outbound routes

The PCE Lutèce communicated on the results obtained with the first four beacons at the end of Spring 2016, showing how travel-times were monitored in preparation for the expressway closure. These received a rather warm welcome, especially given the relatively modest level of funding involved.

The Author then argued that if more funding could be allocated, it would allow to monitor inbound travel-times from three Paris West main entrances to the already monitored city center origin-destinations, and outbound travel-times from the aforementioned central city origin-destinations to the main interchange at Bercy, which is the natural destination to most traffic flowing from St Germain or the Quais Rive Droite.

Additional funding was then made available by the City Administration, this time for four beacons, in June 2016.

It was too late to assess travel-times before the expressway closure, but nevertheless they would allow a follow-up on the travel-times trends, in order to quantify how traffic conditions would evolve.

The preparatory study was carried out in June and July 2016, but some issues with funding allocation, along with the annual leave of most personnel during August, meant that the beacons were only installed on October 26th, 2016. The setup procedure went on very smoothly.

In the West, three city gates of Paris were equipped: Porte Maillot, Porte de Saint-Cloud and Quai Saint-Exupéry. Porte de Saint-Cloud ended up being redundant with Quai Saint-Exupéry, and was therefore not studied.

In the East, the outbound Quai Rive Droite was equipped with a beacon, a few hundred meters before the Bercy interchange complex between the ringway and the A4 motorway.

Four inbound origin-destinations were therefore monitored from October 26th, 2016:

- From Porte Maillot to Concorde (start of QHRD route);
- From Porte Maillot to Assemblée (start of St Germain route);
- From Quai St Exupéry to Concorde (start of QHRD route);
- From Quai St Exupéry to Assemblée (start of St Germain route).

And two outbound origin-destinations:

- From Sully (Quais Hauts Rive Droite) to Bercy;
- From Jussieu (St Germain) to Bercy

Given the distance between the beacons, several routes were possible, and these are investigated through the travel-times distributions, as shown later on.

The closure of a major road arterial across Paris caused intensive political turmoil, and made the assessment of the "experimental" closure even more sensitive. The experience gathered in the Place de l'Etoile study allowed to use the Bluetooth beacons, which were already "well-known". The good reception of the data produced allowed the deployment of additional equipments. The Bluetooth travel-times were becoming a reference indicator for one of Paris biggest traffic-related decisions of the early XXIth century.

Nonetheless, even if in the end the beacon infrastructure provided a working and reliable assessment infrastructure, complementing the legacy traffic sensors, the failure at Châtelet allowed to reinforce the setup process. It also underlined the efforts required for such operations to be carried out, and that even non-intrusive solutions such as the beacons may have its shortfalls.

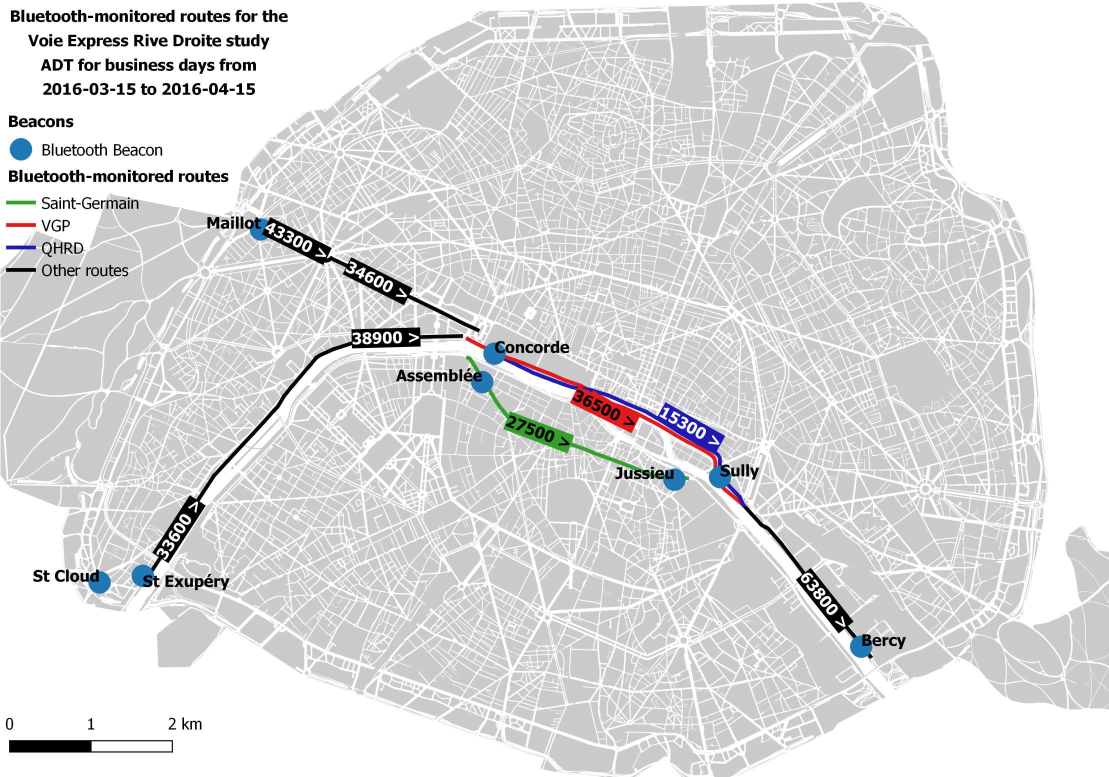

Figure 5.1 – Bluetooth-monitored routes for the Voie Express Rive Droit study, along with their ADT for business days from March 15th, 2016 to April 15th, 2016.

5.3 An operational issue for Bluetooth travel-times: discriminating routes on the Right Bank

The main characteristics of Bluetooth travel-time distributions have already been discussed in the Place de l'Etoile chapter.

An operational concern regarding the beacons setup is route choice, especially on the Right Bank: how to discriminate traffic traveling the same origin-destination pair? In this case, with one origin-destination pair (from Concorde to Sully beacons), and two possible routes (either the QHRD route or the expressway, i.e. the VGP route), and with no beacon to discriminate the two routes?

This section thus investigates the use of Bluetooth travel-time distributions to discriminate route choices: can the travel-time distribution be used to discriminate route choices?

The process, described in the section, involves: 1. identifying the possible routes for the Concorde to Sully origin-destination; 2. drawing the Bluetooth travel-time distribution; 3. investigating the factors, known from previous studies, that influence the distribution, namely time variations and equipment type.

The data used covers the business days from March 15th to April 15th, 2016.

5.3.1 Possible routes for the same origin-destination pair

The first step, trivial at first sight, in using the Bluetooth travel-time distribution to discriminate routes of an origin-destination pair is to identify the possible routes.

The beacons at Concorde and Sully define an origin-destination that could be traveled, before July 2016, by two distinct routes, and some combinations of both:

- by the expressway (referred to as VGP route);
- by the Quais Hauts Rive Droite (referred to as Quais Hauts or QHRD route);
- by a combination of the two, using either one of the two expressway exits or the expressway entrance on the considered central section.

Nevertheless, given the position of the two beacons, the reasonable assumption was made that people that followed the studied origin-destination chose to stick to either the expressway or the Quais Hauts. The Quais Hauts at the Sully beacon leads inevitably to the expressway (Mazas entrance ramp), or else to a U-Turn, and people that turned off the expressway at one of the two exits have little to no reason to go by the Sully beacon, as this would force them to join back the expressway. The combination the other way is more plausible, i.e. traveling on the Quais Hauts when coming from Concorde, and joining the expressway at the entrance ramp about 500 meters up from the Sully beacon. Nevertheless, this route closely resembles the "Quais Hauts only" option, as only the last 500 m are traveled on the expressway, where traffic lights installed in September 2012 are placed. Moreover, the frequent clogging of the entrance ramp meant it was quicker to stay on the Quais Hauts until Mazas. Therefore, traveling these last 500 m either by the Quais Hauts or the expressway makes little to no difference for the resulting travel-time.

The study ends up considering either Quais Hauts or the expressway route for the Concorde to Sully origin-destination.

No beacon being available to discriminate between the two routes, only the travel-time distribution T could possibly be of help.

5.3.2 The origin-destination travel-time distribution

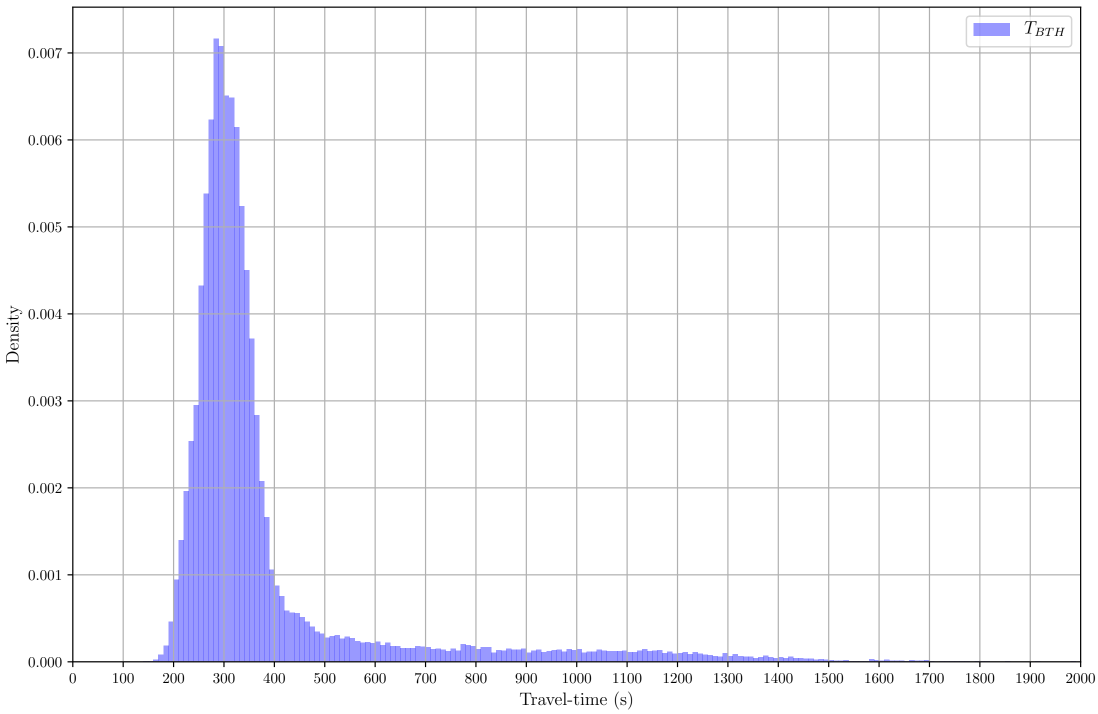

Figure 5.2 – Travel-time distribution, over Concorde to Sully origin-destination, for both VGP and QHRD routes. Business days, March 15th to April 15th, 2016.)

The two routes for the Sully to Concorde origin-destination having been defined, the second step is to draw the travel-time distribution from the Bluetooth data records.

Figure 5.2 shows the travel-time distribution for the Concorde to Sully origin-destination, for the business days from March 15th to April 15th, 2016. This is how travel-times are distributed, without any predicate on equipment type or possible route.

The resulting distribution shows two modes, with one very strong peak centered around a travel-time of 300 s. Crudely, the peak can be analyzed by taking travel-time values less than or equal 400 s: these values center around a median value of 299 s and a mean of 300 s, with low dispersion, the inter-quartile range being 62 s and the standard-deviation 44 s.

The second peak is less striking, barely a bulge around 420 s, followed by a long tail ending around 1300 s.

It is known "from experience" that the expressway, by its characteristics, had a very reliable travel-time, and that the Quais Hauts, as a signalized arterial with frequent congestion at the strategic bridge heads it crosses, would show a more dispersed travel-time. Again, crudely, considering travel-time values above 400 s, yields a median travel-time of 687 s, a mean at 800 s, a standard deviation at 460 s and an inter-quartile range of 536 s. This illustrates the great dispersion of these upper travel-time values.

We hint that the first peak are the expressway travel-times, and the second the Quais Hauts travel-times.

One could argue that this crude analysis, done by setting a threshold at 400 s, could be sufficient to estimate travel-times on both routes. Nevertheless, if the travel-time for the QHRD route peaks at 400 s, this means that some of its travel-times are somewhat lower than 400 s, especially on off-peak periods, knowing that there is a green wave all along. Hence both underlying route-specific travel-time distributions are mixed, especially for values below 400 s, and only a more thorough analysis can sort it out.

However, before carrying such analysis, one must make sure that the two modes of the distribution are not caused by the two main factors investigated in previous studies: either a heterogeneous population of equipments (recall the Place de l'Etoile and the headsets, that are in fact two-wheelers), or by a strongly varying distribution through the time of day.

5.3.3 Ruling out heavy time variations

The first factor to investigate is the influence of time variations. The two modes displayed by the overall travel-time distribution may be caused by strong variations between off-peak and peak-periods of the travel-time.

Figure 5.3 shows the time series for the travel-time over the Concorde to Sully origin-destination. It shows a great stability of the distribution in terms of time, of both the 25th, 50th and 75th percentile, with some alteration at night due to the smaller number of records. The major variation appears between 16:00 and 19:00, with the 75th percentile peaking around 18:00. For the 17:00 to 18:00 time period, the IQR stands at 6.2 min, whereas it is at 1.5 min for the whole dataset. Therefore strong variations in the distribution are concentrated in this very small time-frame.

Plotting the histograms for the 16:00 to 19:00 time period vs. the rest of the day and the overall distribution (Figure 5.4) shows that the rest of the day and overall distributions are nearly identical, and fairly close in shape with the 16:00 to 19:00 one. The 16:00 to 19:00 distribution holds the same general characteristics as the distributions for the rest of the day, and the overall one. It nevertheless has higher travel-times than for the rest of the day and overall ones, remaining on the same grounds for the "major peak", but with a fairly more important tail. The tail is nevertheless not constantly decreasing : it has a bulge between 600 and 700 s, but then a second peak around 1100-1200 s. We still have the illustration that two competing routes coexist, with one slower than the second and with a more spread-out travel-time, both distributions being "shifted" due to the increased traffic, relatively to the overall distribution. In terms of population, the 16:00 to 19:00 distribution accounts for nearly 25 % (10,083) of the total number (37,977) of records. Therefore the "weight" of the three-hour long distribution within the 24-hour one is substantial. The time variations contributed to the previously observed "bulge" within the overall distribution, previously setting a threshold at 400 s to separate travel-time recorded on QHRD vs VGP routes. It appears to be closer to 600 s, as heavier traffic on the VGP route causes a higher tail of the "gaussian-like" peak.

Time variations do not alone explain the two modes of the overall travel-time distribution, as the two-modes characteristic remains when travel-time increase during the 16:00 to 19:00 evening peak period.

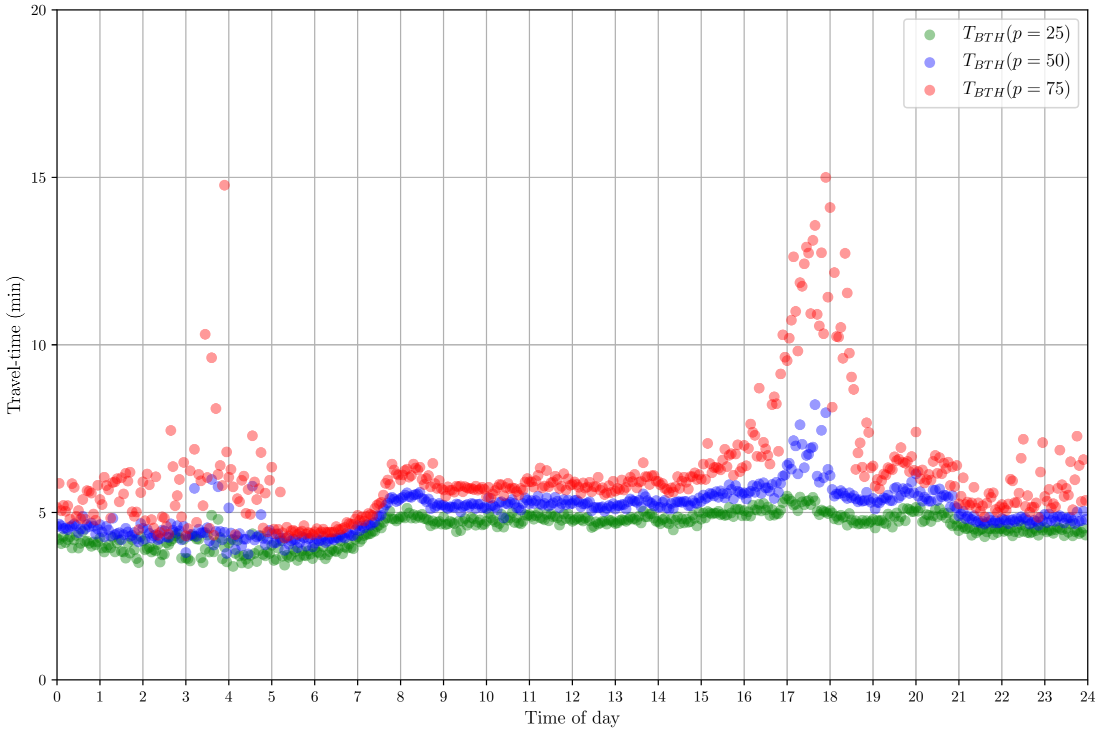

Figure 5.3 – Travel-time 25th, 50th and 75th percentile per t_{03min} interval, over Concorde to Sully origin-destination, for both VGP and QHRD routes. Business days, March 15th to April 15th, 2016.

5.3.4 Ruling out equipment types influences

The second factor to investigate regarding the two-modes of the travel-time distribution is the variation in equipment type, as these may characterize different underlying vehicle fleets. This aspect was striking for the Etoile study, and therefore had to be checked for this origin-destination pair.

The equipment types are in line (Figure 5.5) with the Etoile study, the four most represented equipment types, accounting for 46,532 out of the 48,060 records, being:

- Audio/Video: Hands-free Device (31,958 records);
- Phone: Cellular (5,776 records);
- Phone: Smart phone (4,798 records);

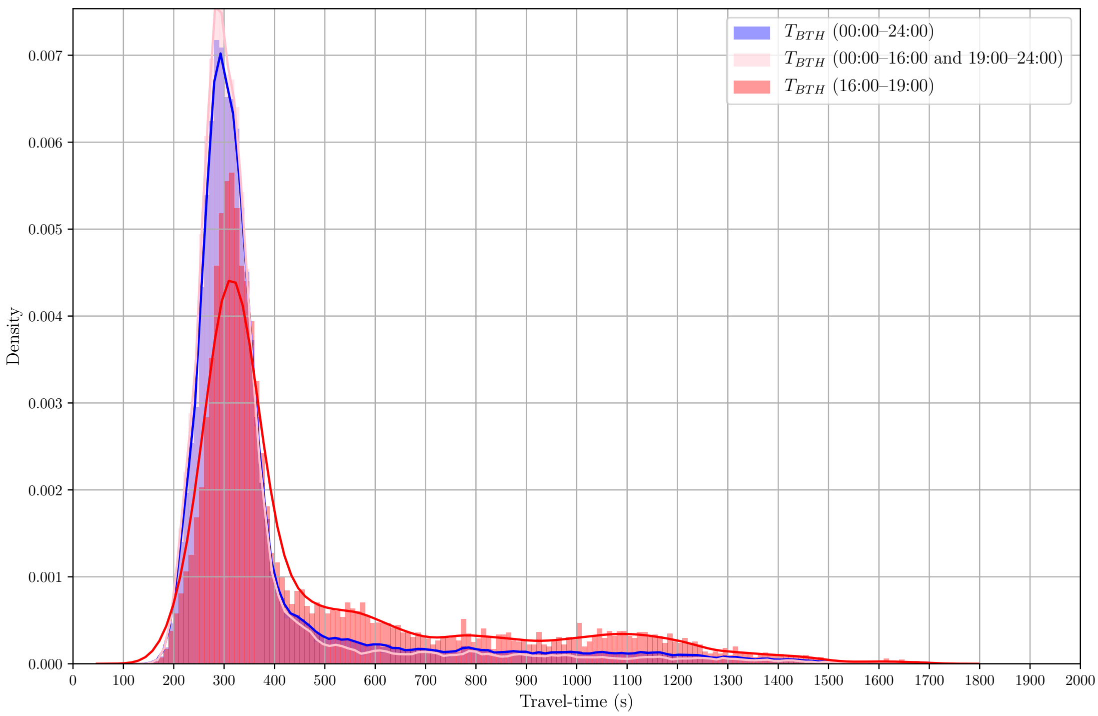

Figure 5.4 – Travel-time distribution, compared between 16:00 to 19:00, the rest of the period, and all-day, for both VGP and QHRD routes. Business days, March 15th to April 15th, 2016.

- Audio/Video: Wearable Headset Device (4,000 records).

The first three items of the types listed above will be referred to as the "Phone" group (42,536 records), and the last one as the "Headset" group (4,000 records).

Plotting the travel-time distribution for each of these four equipments (Figure 5.6) shows that the Wearable Headset devices stands out (with a median travel-time of 256 s) of the three other types of equipments plotted (with a median travel-time of 317 s). The chance is that these are two-wheelers, as the QHRD route doesn't have a dedicated bus lane all-way long, and that it cannot deliver such a fast travel-time (faster than the expressway !) even to authorized vehicles (buses or taxis).

The Headset peak being lower than the Phone peak, plus its far lower population (number of records), means it has little to no effect on the travel-time values above 400 s that are of interest regarding the second mode of the over-all distribution.

5.3.5 Two underlying travel-time distributions for two distinct routes

The two factors, time variations and equipment types, have an influence on the overall travel-time distribution. Nonetheless, the analysis carried out and reasonable assumption show that they can be ruled out as the major cause of the two modes of the distribution.

The most probable cause remaining to explain the distribution's aspect with two modes is the existence of two routes to complete the origin-destination.

The empirical distribution illustrates the two routes that constitute the Concorde to Sully origin-destination pair: the expressway (VGP) and the Quais Hauts (QHRD) routes.

Let T is the random variable describing the travel-time on the origin-destination, T^{QHRD} the travel-time on the QHRD route, and T^{VGP} the travel-time on the VGP route. Let their respective cumulative distribution functions (c.d.f.) be F_T, $F_{T^{QHRD}}$ and $F_{T^{VGP}}$, and their re-

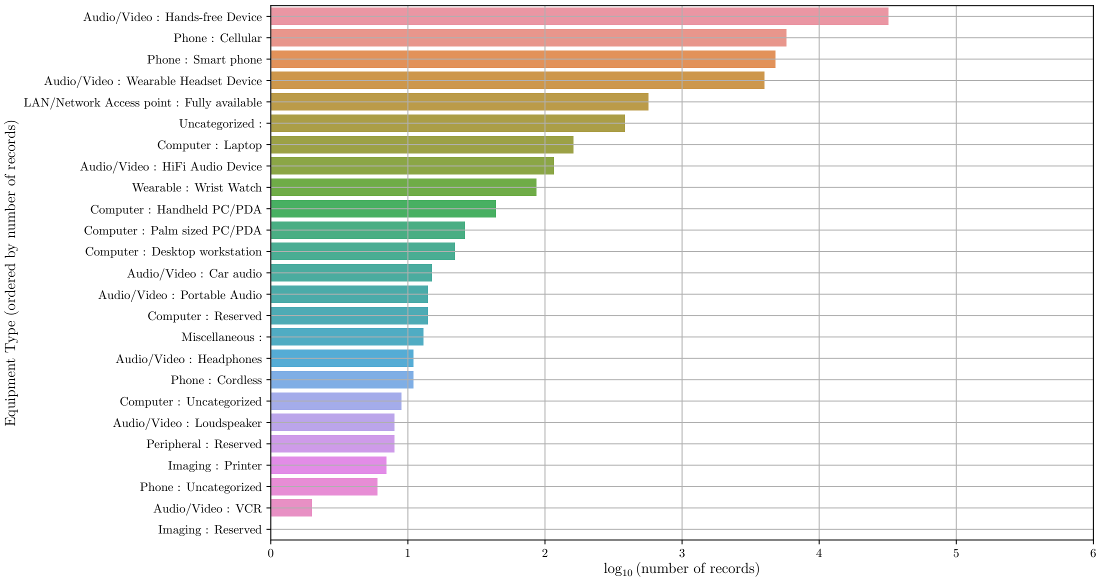

Figure 5.5 – Number of records by equipment type, for both VGP and QHRD routes. Business days, March 15th to April 15th, 2016.

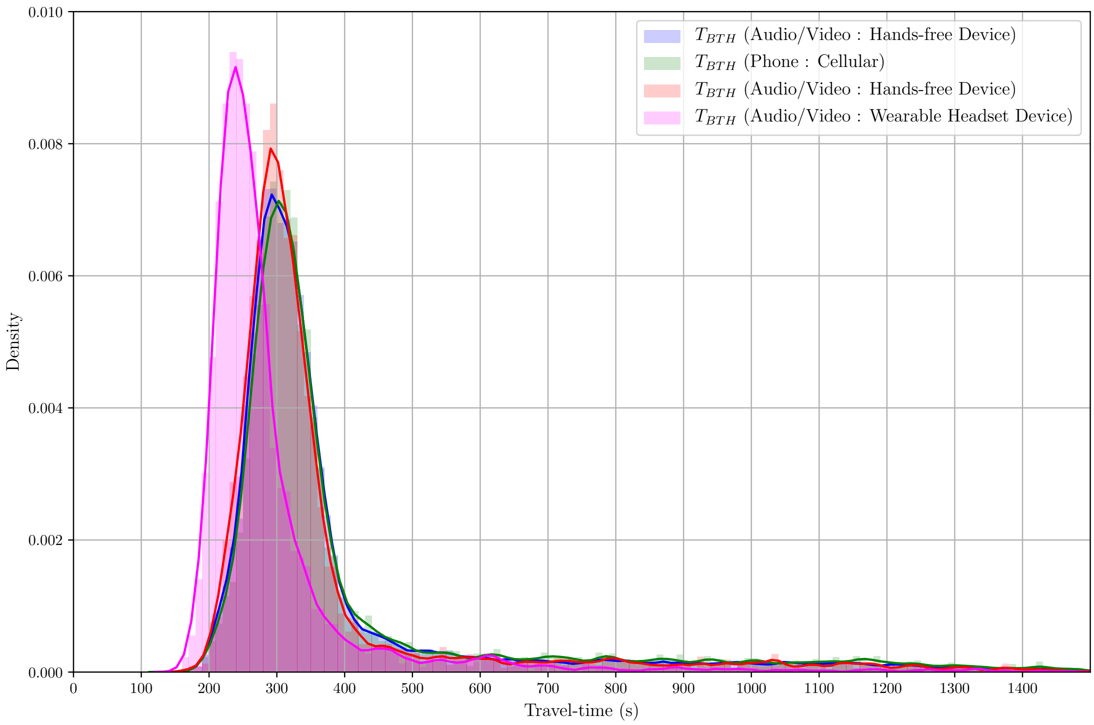

Figure 5.6 – Travel-time distributions of the four main types of equipments, for both VGP and QHRD routes. Business days, March 15th to April 15th, 2016.

spective probability density functions (p.d.f.) f_T, $f_{T_{QHRD}}$ and $f_{T_{VGP}}$. F_T results in the convex combination of $F_{T_{QHRD}}$ and $F_{T_{VGP}}$, with a coefficient α, $0 \leqslant \alpha \leqslant 1$:

$$F_T = \alpha \times F_{T_{QHRD}} + (1 - \alpha) \times F^{T_{VGP}} \tag{5.3.1}$$

Among the classic analytic probability distribution, several have proposed to fit empirical travel-time datasets.

The normal distribution can at first glance be considered a good approximation of travel-time distributions, but some second thought raises some crucial shortfalls: its symmetry, whereas travel-time distributions tend to have a asymmetric tail toward upper values, and most importantly, the normal law considers that negative values can occur with a non-zero probability, which is physically unacceptable. A given route always has a "free-flow travel-time", threshold under which very few vehicles will go on regular operational grounds.

For qualitative reasons (recall the travel-time distributions observed for the Etoile project, or the travel-time distributions studies in the 1950s by BERRY and GREEN [60]) the Author chose a shifted log-normal distribution, which has already been proposed in studies to define travel-times. The usual Log-Normal law equals zero at zero, is valid on strictly positive values, and is asymmetric. We will consider a shifted log-normal law, as to reflect the physical limitation of a minimum travel-time. This minimum travel-time can be understood as the "free-flow travel-time". We suppose that the travel-time on each of the two routes follows a shifted log-normal distribution, of c.d.f. F and p.d.f. f, taking in input three route-specific parameters: μ_i, σ_i and $t_{\min,i}$, i designating either the QHRD or VGP route. Note that despite their labels, μ_i and σ_i are not the mean and standard-deviation of the law.

For the travel-time c.d.f. on the QHRD route $F_{T^{QHRD}}$, of free-flow travel-time $t_{\min}^{QHRD}$ (hence $t^{QHRD} \geqslant t_{\min}^{QHRD}$), under the shifted log-normal law, any value of t^{QHRD} below or equal to $t_{\min}^{QHRD}$ has probability zero, and any value above it has a non-zero probability that follows the log-normal law shifted by $t^{QHRD} - t_{\min}^{QHRD}$.

The resulting α-convex combination of two shifted log-normal c.d.f. is:

$$F_T = \alpha \times F(\mu^{VGP}, \sigma^{VGP}, t_{\min}^{VGP}) + (1-\alpha) \times F(\mu^{QHRD}, \sigma^{QHRD}, t_{\min}^{QHRD}) \tag{5.3.2}$$

with

$$F(\mu, \sigma, t_{\min}) = \frac{1}{2} + \frac{1}{2}\text{erf} \times \left[\frac{\ln(t - t_{\min}) - \mu}{\sqrt{2}\sigma}\right] \tag{5.3.3}$$

and its p.d.f.f being:

$$f(\mu, \sigma, t_{\min}) = \frac{1}{(t - t_{\min})\sigma\sqrt{2\pi}}\ e^{-\frac{(\ln(t - t_{\min}) - \mu)^2}{2\sigma^2}} \tag{5.3.4}$$

with erf the Gauss error function defined as follows:

$$\text{erf}(x) = \frac{1}{\sqrt{\pi}} \int_{-x}^{x} e^{-t^2} dt \tag{5.3.5}$$

The Shifted Log-Normal law was fitted numerically over the empirical cumulative frequency function of travel-times [111], which does least-square curve fitting with the commonly-used Levenberg–Marquardt algorithm.

C.d.f. curves were used instead of p.d.f. for physical reasons: the distance between the empirical and tested distributions on a cumulated frequency axis can be directly graphically interpreted as a Kolmogorov-Smirnov distance, whereas density curves only yields a curve that "goes through the scatter at best".

The fit yields satisfactory results, with a χ^2-statistic of 0.049 and reduced χ^2-statistic of 0.000.

The purpose was not to demonstrate that travel-times follow a shifted log-normal distribution, but to describe, using a probability distribution with an explicit analytical formulation, the two modes shown by the empirical data. Each of the two modes being described, it is then possible

route	QHRD	VGP
α	0.87	
μ	5.09	6.25
σ	0.32	0.58
$t_{\min}$	140	350
average	966	310
standard deviation	391	57
20th percentile	670	264
25th percentile	700	270
median	870	302
75th percentile	1120	341
80th percentile	1200	352
IQR	420	71

Table 5.1 – Coefficients and descriptive statistics for the estimated shifted log-normal law of each QHRD or VGP route. Business days, March 15th to April 15th, 2016.

to draw estimates of the respective distributions of the QHRD and VGP travel-times.

Table 5.1 presents both the estimated parameters of both routes, and the resulting descriptive statistics.

It translates the importance of the VGP route upon the QHRD route within the travel-time distribution, with an α of 0.87: the VGP route accounts for 87 % of the origin-destination travel-time records.

The model implies a median travel-time of 302 s on the VGP route, and of 870 s on the QHRD route. This is coherent with the expressway attractiveness for crosstown itineraries in respect with the QHRD signalized routes, the median travel-time of the latter being almost three-times higher than the one of the former.

The model also gives insight into the reliability of the travel-time, which can be quantified by the various dispersion indicators, like the standard deviation or ranking. For the VGP route, the standard deviation stands at 57 s, and the inter-quartile range at 71 s, translating a squeezed distribution, centered on its median value. On the opposite, the QHRD route holds a standard deviation of 391 s and an inter-quartile range of 420 s: travel-times on the QHRD form a highly stretched distribution.

In other words, the travel-time on the VGP route is much more reliable than on the parallel QHRD route. The VGP route delivered a median travel-time of 57 s, with IQR-estimated possible variations of 71 s around it, whereas the QHRD route delivered a median travel-time of 870 s with high IQR-estimated variations of 420 s.

The distribution of Bluetooth travel-time taken over an origin-destination and including several competing routes can be used to discriminate route choices, using its different modes. Nonetheless, care must be taken, as two factors directly influence the travel-time distribution and may be the source of some modes: the time variations, and the categories of equipments.

Careful reasoning must be applied to rule out the effect of these two factors on the travel-time distribution.

In the case of Concorde to Sully, the route choice remained quite constant throughout the day, and time variations remained "reasonable": only the evening peak saw higher travel-times but only shifted the distribution without modifying its general aspect showing two modes. The equipment types, namely the Phone and Headset groups, did affect the travel-time distribution, but not in the range of values of the second mode. The Phone group, by far larger than the

Headset, was the one shaping the general travel-time distribution.

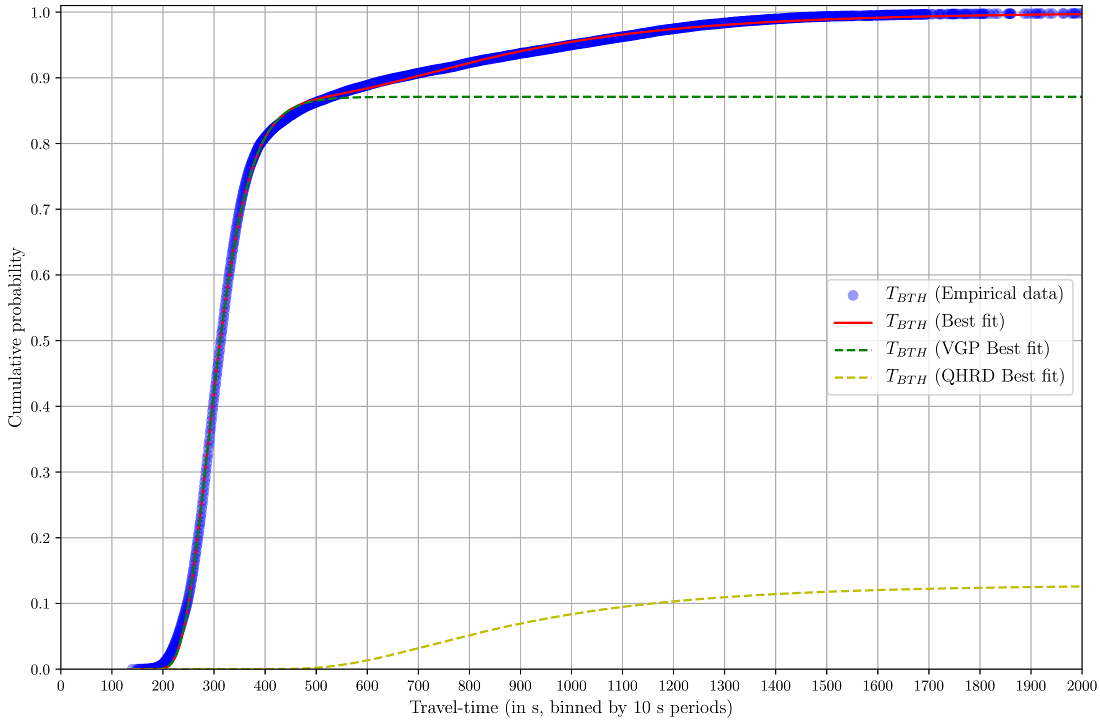

Figure 5.7 – Travel-time cumulative distribution function on the Concorde to Sully origin-destination, with the empirical measurements and the fitted theoretical shifted log-normal laws for each route (QH or VGP) and the convex combination of both (QH and VGP)

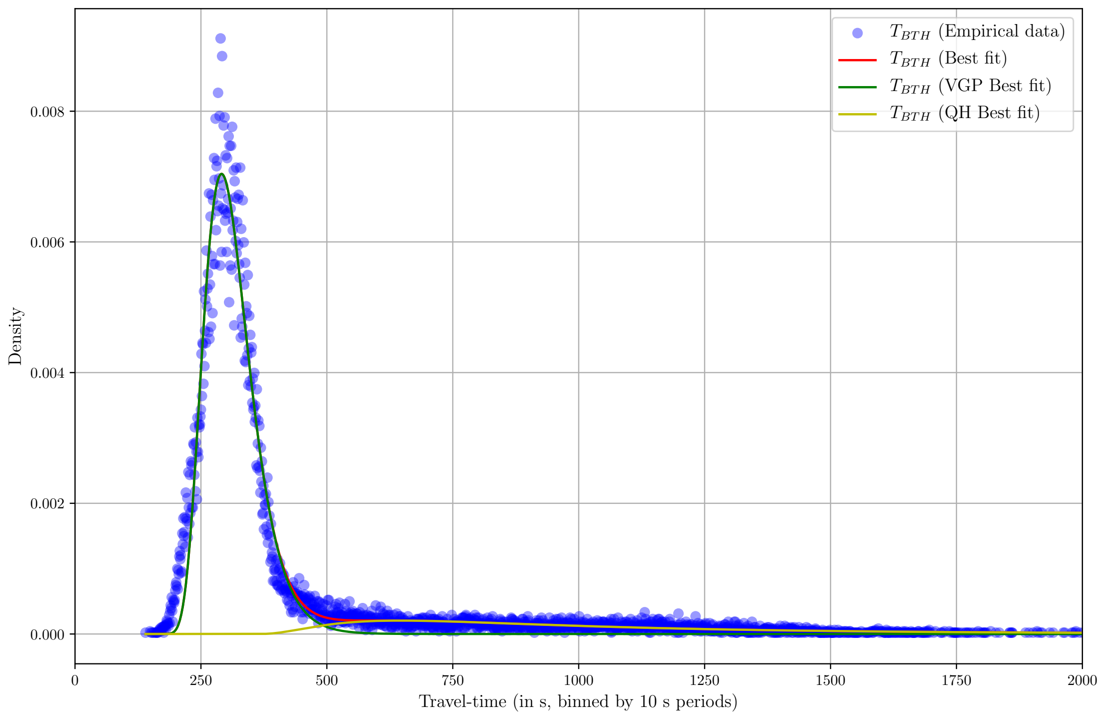

Figure 5.8 – Travel-time probability density function on the Concorde to Sully origin-destination, with the empirical measurements and the fitted theoretical shifted lognormal laws for each route (QH or VGP) and the convex combination of both (QH and VGP)

5.4 Bluetooth detection: free-flow travel-time and traffic penetration

The Bluetooth dataset, and not only travel-time, can serve other purposes than travel-times for assessing traffic-related policies. Both cases are investigated through the Assemblée to Jussieu origin-destination pair, which only consists of one route, the Boulevard Saint-Germain. The Boulevard Saint-Germain is a one-way arterial with synchronized traffic-lights. The period of analysis is the business days from March 15th, 2016 to April 15th, 2016.

A first question is the minimum speed over a route: can the Bluetooth dataset be used to find the free-flow travel-time? This has direct consequences on considerations such as the speed limit: do drivers, in free-flowing conditions, abide to the speed-limit?

A second question is how Bluetooth equipments penetrate the traffic: is there a statistical law governing the occurrence of Bluetooth equipments over a route?

5.4.1 The importance of free-flow travel-times

5.4.1.1 Background on free-flow travel-time and free-flow space-mean speed

The free-flow travel-time, and its reciprocal the free-flow (space-mean) speed, is an important variable. It is the time it takes for the flow of traffic to complete a specific journey when it is not impeded by congestion. This means all vehicles making up the flow of traffic travel at their desired speed, and the only factors affecting their speed is the infrastructure layout but not other vehicles.

Sometimes overlooked because of its trivial aspect and the historical focus on congestion, it nonetheless serves multiple purposes.

For traffic management aspects, it defines the best level of service offered by a road network, and is therefore an input to the computation of delays. A journey travel-time T can be defined as the sum of the free-flow travel-time T_{ff} and the delay T_d:

$$T = T_{ff} + T_d \tag{5.4.1}$$

Directly computing a delay T_d is often complicated, but computing it as the difference between the actual travel-time (T) and the free-flow travel-time (T_{ff}) is a lot easier:

$$T_d = T - T_{ff} \tag{5.4.2}$$

For the theory of traffic, of course linked to traffic management issues, the free-flow travel-time T_{ff}, and often its reciprocal, the free-flow space-mean speed V_{ff}:

$$V_{ff} = \frac{1}{T_{ff}} \tag{5.4.3}$$

is a fundamental parameter of the fundamental diagram, or flow-concentration relationship, defining the characteristics of the free-flow regime and of the critical point.

Another aspect of the free-flow speed is the speed-limit issue: the speed-limit v_{lim}, and the associated travel-time T_{lim}. When not impeded by congestion, drivers should abide to the speed-limit, and therefore their journey travel-time should follow the constraint:

$$T \geqslant T_{ff} \geqslant T_{lim} \tag{5.4.4}$$

or, in terms of space-mean speeds:

$$V \leqslant V_{ff} \leqslant V_{lim} \tag{5.4.5}$$

As a first approximation, like in some traffic models or journey planners, the speed-limit V_{lim} is taken as the free-flow speed V_{ff}:

$$V_{ff} = V_{lim} \Rightarrow T_{ff} = T_{lim} \tag{5.4.6}$$

Nonetheless, in an urban environment, the main factors behind the free-flow travel-time are not only the speed-limit, but also the width of the road and the signal timing, as already shown by Berry and Green in the 1950s [60].

5.4.1.2 Preliminary analysis of the Bluetooth travel-times on Bd Saint-Germain

Before getting any further into the analysis of the travel-time characteristics of bd St Germain, a preliminary analysis of the general travel-time distribution and the underlying equipment types is needed, in line with the previous work.

The bar plot of the number of records per equipment type, Figure 5.9, shows that the first four equipment types are present in the same order, in terms of importance, as in previous analyses. Out of 23,382 records for the considered period, the split between the first four types, and Phone and Headset groups, is as follows:

- Phone group. Audio/Video: Hands-free Device (17,513 records);
- Phone group. Phone: Cellular (2,695 records);
- Phone group. Phone: Smart phone (1,543 records);
- Headset group. Audio/Video: Wearable Headset Device (645 records).

The number of headset devices is far lower than the first three equipment types, below 1,000, compromising meaningful travel-time statistics on the Headset groups.

Figure 5.10 plots the travel-time distributions for these four types of equipments: the kernel density estimate shows that equipments in the Phone group, accounting for 21,751 records, follow the same travel-time distribution, whereas the Headset group, accounting for 645 records, suffers from a low number of records. For the Headset group, it hints a trend different from the Phone group, but the analysis cannot be pursued much given the available data. The median travel-time for both groups remains close (692 s for the Phone vs. 700 s for the Headset), but the interquartile range of the Headset group is higher (465 s) than the Phone's (381 s). It is nonetheless reasonable to assume that the greater dispersion can be as much attributed to the two-wheeler assumption drawn in the other cases (Etoile, or QHRD-VGP routes) than to the low sample of the group.

The time series of records number, Figure 5.11, shows a clear time-dependent trend of the Phone group, whereas the Headset group remains with a very low number of records throughout the day.

In the end, this analysis shows that further study of the travel-time distribution is not impeded by significant underlying subpopulation differences, given the very low number of Headset equipments that are recorded on the entire route.

5.4.1.3 Characterizing the arterial free-flow speed

Characterizing the arterial free-flow speed relies on both the distribution of travel-times, described above, and its time series. Figure 5.12 shows, following the time of day, the distribution

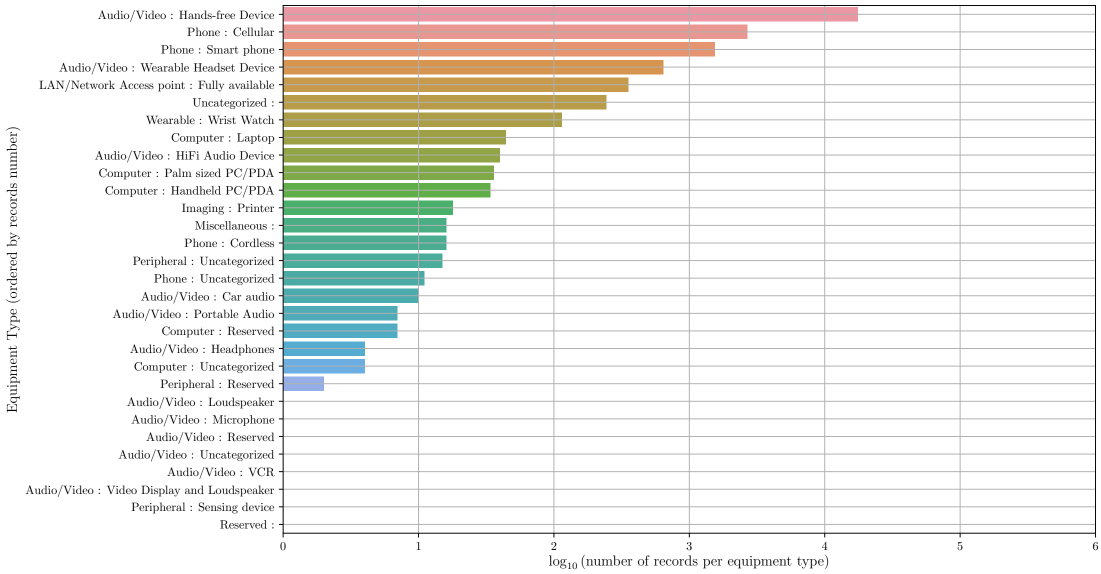

Figure 5.9 – Number of records by equipment type on bd St Germain. Business days, March 15th to April 15th, 2016.

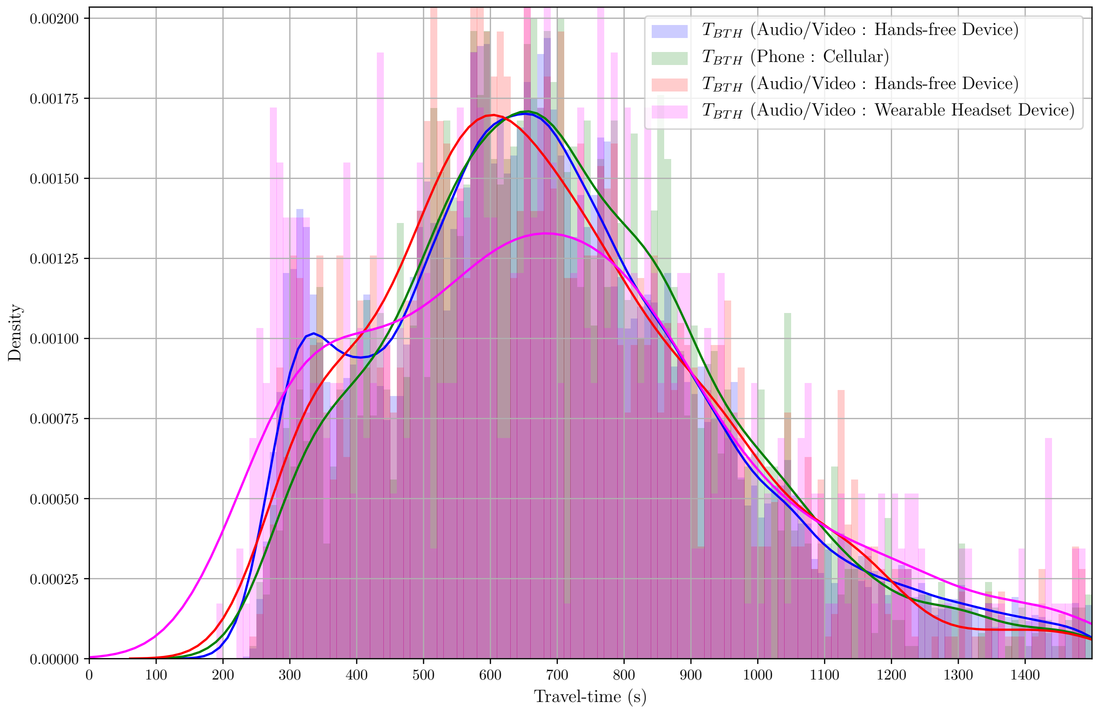

Figure 5.10 – Travel-time distributions of the four main types of equipments, for both VGP and QHRD routes. Business days, March 15th to April 15th, 2016.

of the 0th (or minimum), 25th, 50th and 75th percentiles of the travel-time distribution for the Phone group. Each percentile is computed per t_{03min} slot, over the business days from March 15th to April 15th, 2016.

During the night, between 00:00 and 07:00, the 50th and 75th percentiles show an important dispersion, which can be explained by the very low number of total records collected (total under 15 records per interval at night for the whole reference period, whereas this above 40 during daytime).

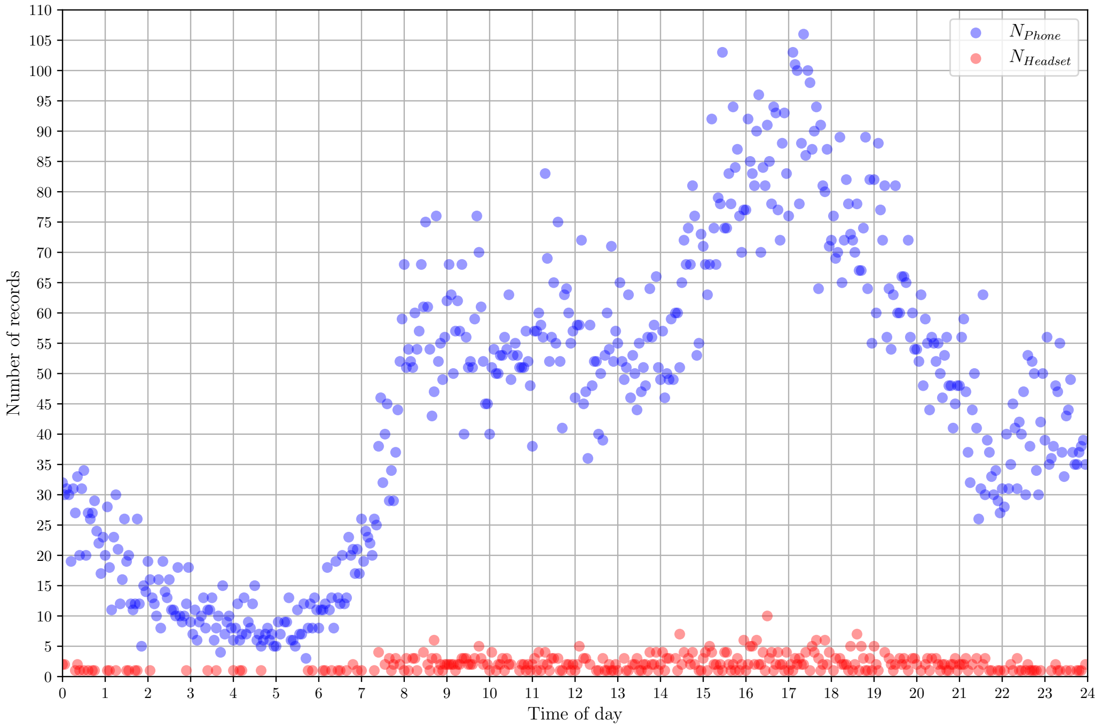

Figure 5.11 – Total number of Bluetooth records per 3min slots, and per group of equipment (phone and headset). Business days from March 15th to April 15, 2016.

The minimum travel-time remains very stable throughout the night (inter-quartile range of 23 s), at a median value[2] of $\widetilde{T_{min}} = 277$ s, which translates into a corresponding minimum flow speed V_{min} of:

$$V_{min} = \frac{L}{T_{ff}} = \frac{3300 \text{ m}}{277 \text{ s}} \approx 11.9 \text{ m.s}^{-1} \approx 42.9 \text{ km.h}^{-1} \tag{5.4.7}$$

Likewise, the 25th percentile remains very stable throughout the night (inter-quartile range of 38 s), at a median value of $\widetilde{T_{p=25}} \approx 316$ s. This travel-time corresponds to a flow speed $V_{p=25}$ of:

$$V_{p=25} = \frac{L}{T_{ff}} = \frac{3300 \text{ m}}{316 \text{ s}} = 10.4 \text{ m.s}^{-1} \approx 37.6 \text{ km.h}^{-1} \tag{5.4.8}$$

Higher percentiles are too dispersed to be meaningful.

The stability of these two statistics is associated with a light, non-congested traffic, as the flow and occupancy recorded by the sensors is well below the thresholds usually associated with disturbances.

Either the minimum T_{min} or $T_{p=25}$ travel-times could be taken as estimates of the free-flow travel-time T_{ff}. It is tempting to take the minimum value, since it offers a lower inter-quartile range than the 25th percentile. Nonetheless, the minimum value is always an extremal case, whereas the 25th percentile accounts for 25 % of the Bluetooth records. Hence, as a trade-off between a minimum value, the population and stability, the Author chose the 25th travel-time percentile, $T_{p=25}$, and its median value, $\widetilde{T_{p=25}}$, as the best estimate for the free-flow travel-time T_{ff}:

$$\widetilde{T_{p=25}} \approx T_{ff} \Rightarrow V_{p=25} = V_{ff} \tag{5.4.9}$$

The value of V_{ff}, 37.6 km.h^{-1}, i.e. nearly 40 km.h^{-1}, raised a few eyebrows among some of

[2] X being a variable, $\widetilde{X}$ is the median of its values x.

the PCE Lutèce staff, who felt the value was off course to the "general feeling" they drew from their experience. A shortfall of the Bluetooth equipments was therefore hinted.

Further investigation by the Author upon the traffic situation, at night, on Bd St Germain, showed that the lights are perfectly synchronized along the corridor from begin to end, at a green-wave speed of 40 km.h^{-1} with a time bandwidth at least 15 s large.

That specific setup had become unknown of, and the "general knowledge" thought was that there was a break of coordination at some point on the boulevard, especially at a key intersection with the South to North main arterial, the Bd St Michel, that wouldn't have allowed such a travel-time.

In fact, the driver can then adapt its speed to the traffic light's green wave, stick to it, and unless encountering impeding vehicles, journey from start to end without stopping.

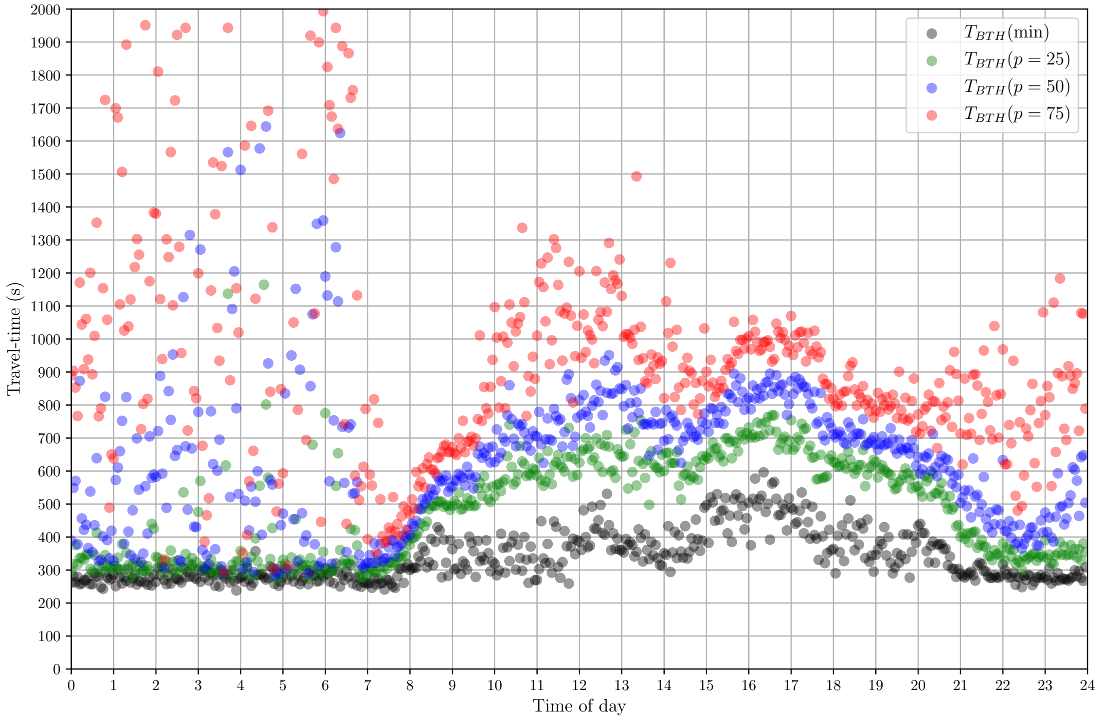

Figure 5.12 – Travel-time minimum, 25th, 50th and 75th percentile per t_{03min} interval, over bd St Germain, for phone group of equipments. Business days, March 15th to April 15th, 2016.

5.4.2 Travel-times on St Germain: distribution of Bluetooth headways

The way Bluetooth equipments penetrate the traffic is a key question. Nonetheless, answering it is far from trivial.

The daily number of Bluetooth records for the origin-destination, when compared to loop-based traffic flow, is low. As the flow is only counted at the loop's position, the ratio of Bluetooth records number over the Assemblée to Jussieu route over loop's data does not yield the Bluetooth penetration rate. Indeed, people counted at the traffic loop location can have their Bluetooth activated when passing by the Assemblée beacon, but turn off the boulevard before reaching Jussieu, and therefore not be counted in end-to-end travel-time statistics. This is a major hurdle in estimating the actual Bluetooth penetration rate: the exact number of vehicles traveling the Boulevard from end-to-end would have to be known, and equipments allowing such measures would be redundant with the Bluetooth beacons, and a lot more expensive (like Automatic

Plates Recorders).

The purpose here focuses on whether a simple statistical model, namely the Poisson process, can be applied to the occurrence of Bluetooth detection. The Author, here, was in a way inspired by the work of Adams [21], who described motor traffic as a Poisson point process in the 1930s.

5.4.2.1 The rare event assumption for Bluetooth-enabled device occurrence

Not all vehicles passing by the beacons are equipped with a Bluetooth-enabled device. In a first estimate, it can be assumed that the occurrence of a Bluetooth-enabled device among the vehicles traveling the Assemblée to Jussieu origin-destination, considered as a "rare event", is a Poisson process (or a process that resembles it).

A Poisson process means that the duration between two events follows an exponential law, the reciprocate being also true.

The event E considered here is the detection of the same MAC address a at two beacons o (at time t_o) and d (at time $t_d > t_o$) that define an o-d pair. The event translates into the database as a travel-time record (o, d, a, t_1, t_2), the travel-time $T(o, d, a, t_o, t_d)$ being:

$$T(o, d, a, t_o, t_d) = t_d - t_o$$

Each event E is assumed independent of the others.

For the origin-destination from o to d, we consider two consecutive travel-time records (as saved in the database) $(o, d, a_1, t_o^{a_1}, t_d^{a_1})$ and $(o, d, a_2, t_o^{a_2}, t_d^{a_2})$, with $t_o^{a_1} < t_o^{a_2}$. The two records are consecutive, meaning that for any travel-record with a MAC address $a_3 \notin (a_1, a_2)$, then necessarily $t_o^{a_3} < t_o^{a_1}$ or $t_o^{a_3} > t_o^{a_2}$.

Therefore, for all days from March 15th to April 15th, 2016, the headway $dt(a_1, a_2)$ between two consecutive records is:

$$dt(a_1, a_2) = t_o^{a_2} - t_o^{a_1}$$

5.4.2.2 Approximation by a homogeneous Poisson point process

In a first approximation, the resulting sequence of events E is assumed to follow a homogeneous Poisson point process, i.e. with that the rate of having an event E is constant throughout the period. This assumption implies that the headway between two successive events follows an exponential law. The demonstration is as follows.

The discrete Poisson law p.d.f. is:

$$P(X = x) = \frac{e^{-\mu} \mu^x}{x!} \tag{5.4.10}$$

whose mean is μ and its variance is μ.

The continuous exponential law c.d.f. is:

$$F(t) = 1 - e^{-\lambda t} \tag{5.4.11}$$

and its p.d.f is:

$$f(t) = e^{-\lambda t} \tag{5.4.12}$$

with λ being its parameter. Its mean is $1/\lambda$ and its variance is $1/\lambda^2$

Within a Poisson process, events occur on average at rate of λ per time unit, and there is on average $\lambda \cdot t$ event occurrences per t units of time. λ is known as the rate or intensity of the

Poisson process. X being the random variable describing the number of events occurring in t units of time, the corresponding probability mass function is:

$$P(X = x) = \frac{e^{-\lambda t}\,(\lambda t)^x}{x!} \tag{5.4.13}$$

The probability that no events occur in t units of time is:

$$P(X = 0) = e^{-\lambda t} \tag{5.4.14}$$

Reformulating the previous statement, T being the random variable of the time of the first occurrence, then the probability that no events occur in t units of time is the same as the probability that $T > t$:

$$P(T > t) = P\left(X = 0 \mid \mu \ = \lambda t\right) = e^{\lambda t} \tag{5.4.15}$$

Conversely, the probability that an event does in fact occur during t units of time is:

$$P(T < t) = 1 - P\left(X = 0 \mid \mu \ = \lambda t\right) = 1 - e^{\lambda t} = F(t) \tag{5.4.16}$$

The latter is the Exponential law cumulative distribution function, which, when differentiated relative to t, yields the Exponential law probability density function $f(t) = e^{-\lambda t}$

Getting back to Bd Saint Germain, the stationary Poisson assumption thus means that *dt* follows an exponential law.

Figure 5.13 represents the *dt* headway distribution for the St Germain route, and hints a "roughly" underlying exponential law.

The actual fit of the exponential law, as plotted in Figure 5.14 has a reduced χ^2 statistic of $1055 \gg 1$, which the associated rule-of-thumb says is a rather poor fit.

This means that the observed process is not a homogeneous Poisson process, and that events E (detection of travel-time record) may not always be independents.

Now, can *dt* be approximated by a series of homogeneous Poisson process for periods for which traffic conditions are "constant", i.e., the travel-time distribution is "stable"?

5.4.2.3 A series of homogeneous Poisson point processes for periods of constant traffic conditions

The approximation of *dt* by a series of homogeneous Poisson processes per period of constant traffic conditions relies on the proper definition of such periods.

Figure 5.12 provides the time-series of the travel-time distribution over Bd St Germain, per t_{03min} intervals.

Several periods of "stability" can be identified from the median travel-time value.

The night-time period, from 00:00 to 07:00, travel-time distribution is scattered due to the low population per t_{03min} bin, nonetheless traffic conditions remain homogeneous throughout the night, at free-flow regime.

A more congested regime is considered with the 18:00 to 20:00 period, which shows some stability of the travel-time median.

Some transitional periods, like the ones from 07:00 to 09:00, do not follow traffic conditions stability as the median travel-time sharply variates, and will clearly not satisfy the homogeneous Poisson process assumption.

The night-time data fit, illustrated by Figure 5.15, yields a reasonable but still questionable fit, with a reduced χ^2 statistic at 22, far better than the 24h period one. Likely, the 18:00 to 20:00

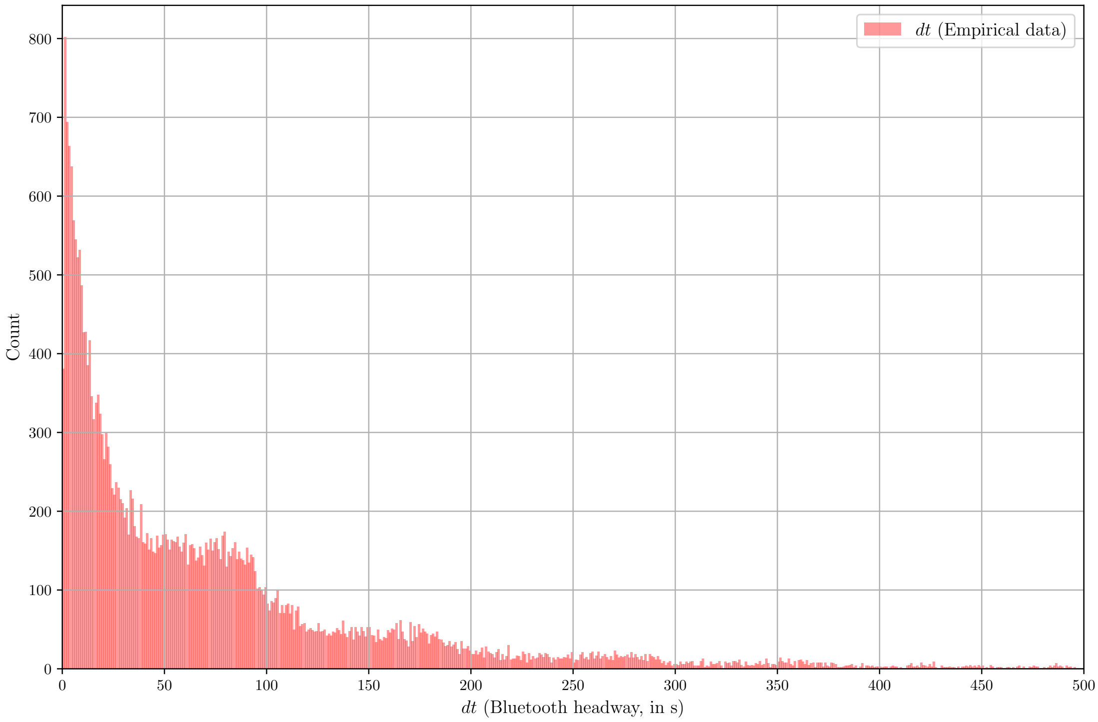

Figure 5.13 – St Germain, from March 15th to April 15th, 2016. dt headway distribution.

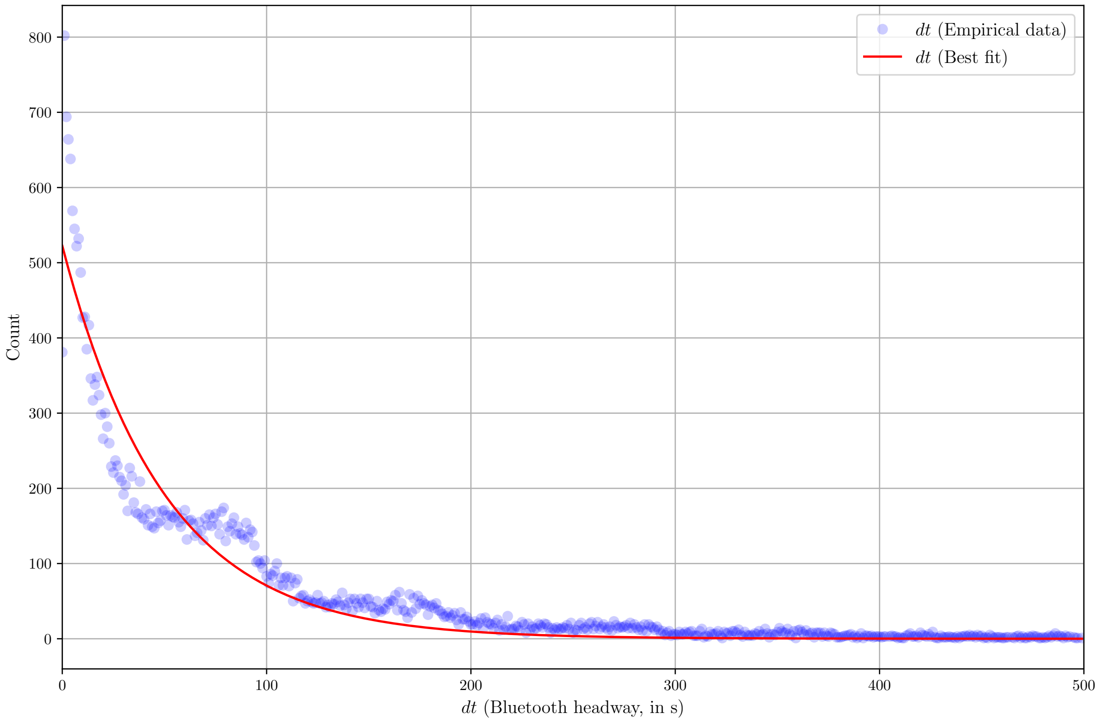

Figure 5.14 – St Germain, business days from March 15th to April 15th, 2016. dt headway empirical measurements and fitted exponential law.

data fit, Figure 5.16, yields a reduced χ^2 statistic at 21. The associated rule-of-thumb states that the fit does not fully explain the data, although the fit is not as poor as when considering travel-times over a 24-hour period.

The Poisson process assumption for periods of traffic stability is therefore reasonable for periods of stable traffic conditions. Nonetheless, the assumptions that support the Poisson process, mainly the independence between events E of Bluetooth equipment occurrence, and the exponential law for the Bluetooth headways, are questionable. The fit to the exponential law is "reasonable", but the independence between events is not necessarily true. Considering traffic on an arterial that's signalized and not always free-flowing, car interaction is the main source of discrepancy, since it cancels the independence assumption, especially if the fleet of Bluetooth-enabled vehicles increases. In case of congestion, the journey of each Bluetooth equipment will therefore be impeded by its neighbors, and there will not be independence between their occurrences.

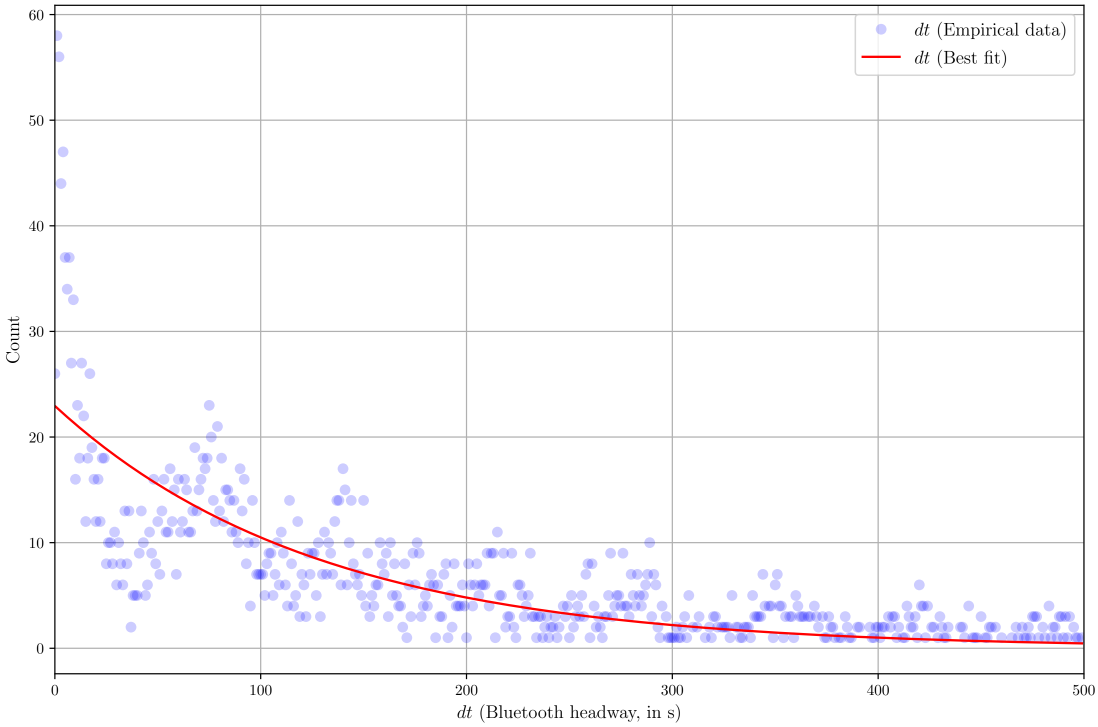

Figure 5.15 – St Germain, business days from March 15th to April 15th, 2016, 00:00 to 07:00 period. dt headway empirical measurements and fitted exponential law.

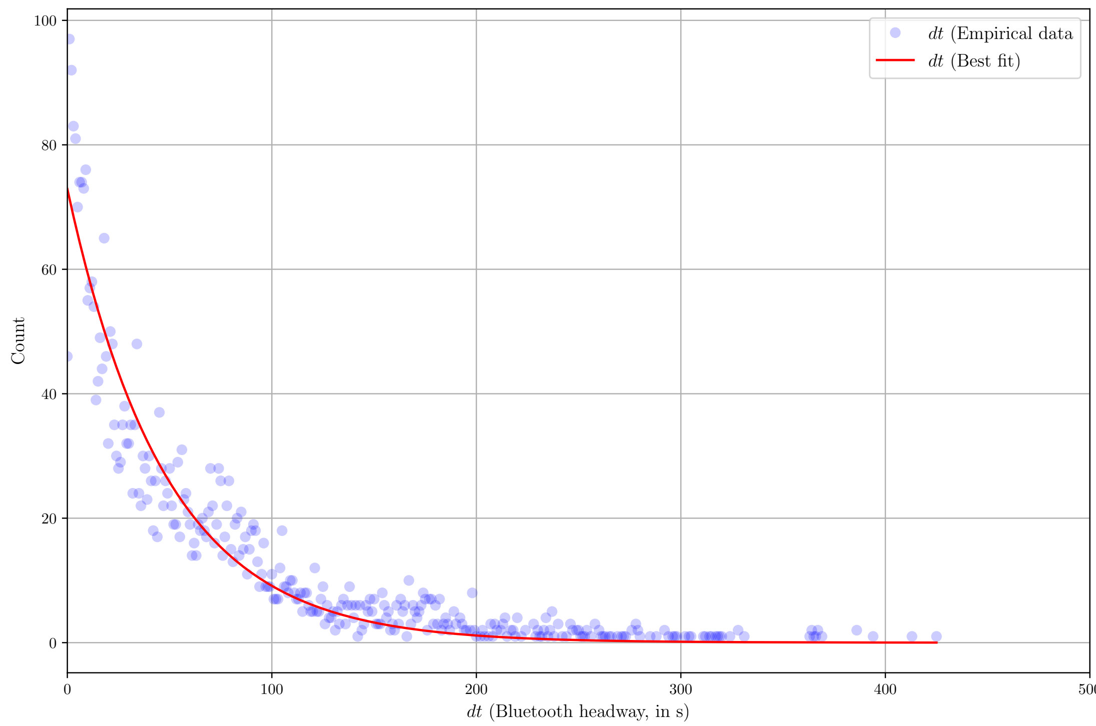

Figure 5.16 – St Germain, business days from March 15th to April 15th, 2016, 18:00 to 20:00 period. dt headway empirical measurements and fitted exponential law.

5.5 From the Traffic Management Center's perspective: how to deal with Bluetooth travel-times and legacy loops data

Since the 1980s, the City of Paris Traffic Management Center has been relying on a pair of loop-based indicators, VKT_{norm} and V_{BRP}, to estimate traffic flow speed and travel-times on its signalized arterials network.

From both the operational and political perpespective, the question of the "continuity" of the indicators is crucial, as these allow to track through time the efficiency and consequences of the decisions made. The indicators are traditionally looked upon for the 07:00 to 21:00 period, at morning (08:00 to 09:00) and evening (18:00 to 19:00) peaks during business days, and on their hourly trend over several business days.

Therefore, the comparison of both loop-based and Bluetooth-based travel-times is a key operational concern: in a case like the expressway closure, some of the arterials followed by the assessment Commission were not equipped with Bluetooth sensors, and therefore their travel-time computations only relied on the traffic loops infrastructure, while others relied solely on Bluetooth due to the unavailability of the loops.

In line with the methodology developed when comparing distributions, Figure 5.17 shows the compared distributions of BRP T_{BRP} and Bluetooth T_{BTH} travel-times, and Figure 5.18 the time series of the two distributions by plotting their respective 25th, 50th and 75th percentiles. Table 5.2 gives the median and IQR of both distributions for different times.

The compared empirical distributions (Figure 5.17) shows the differences between the two distributions. Both are asymmetrical. The BRP travel-time T_{BRP} shows a mono-modal distribution, the mode being centered on the median (601 s), followed by an upper tail but a limited

indicator	period	T_{BRP} (in s)	T_{BTH} (in s)	gap (in %)
median	24 h	601	692	15 %
median	21:00 to 07:00	540	458	-15 %
median	07:00 to 21:00	683	747	9 %
median	08:00 to 09:00	634	512	-19 %
median	18:00 to 19:00	635	706	11 %
IQR	24 h	145	381	162 %
IQR	21:00 to 07:00	69	601	771 %
IQR	07:00 to 21:00	173	328	89 %
IQR	08:00 to 09:00	68	137	101 %
IQR	18:00 to 19:00	143	212	48 %

Table 5.2 – Compared median travel-times and IQR for BRP and Bluetooth

dispersion (IQR of 145 s). The Bluetooth travel-time, on the other hand, shows a more spread distribution, and modes that are less clear: nevertheless, two main overlapping modes can be identified, one for travel-time values below 500 s, and the other, bigger, for travel-time values over 500 s, in which the median value, at 692 s, lies. The dispersion is more important, with an IQR at 381 s.

The time series of the 25th, 50th and 75th percentiles confirms the distribution analysis. The T_{BRP} travel-time 25th, 50th and 75th percentiles remain mostly close to one-another. The Bluetooth travel-time T_{BTH} is scattered at night (low number of records), and shows a gap between the 50th and 75th percentile, which widens during the day, the 75th percentile showing an important variability.

At night, the BRP over-estimates the free-flow travel-time when compared to Bluetooth. During the day, from 09:00 to 20:00, the median BRP and Bluetooth travel-times roughly follow the same trend.

The median BRP holds a minimal threshold value of 500 s, even for times of free-flowing traffic. From 22:00 to 10:00, the median Bluetooth travel-time $T_{BTH}(p = 50)$ stays below 500 s, whereas the median BRP travel-time $T_{BRP}(p = 50)$ sticks to its 500 s threshold value. $T_{BRP}(p = 50)$ then overestimates $T_{BTH}(p = 50)$ by 15 to 20 %. During the day, when traffic is heavier and $T_{BTH}(p = 50)$ is above the 500 s threshold, the $T_{BRP}(p = 50)$ at least follows the trend shown by the Bluetooth. Nevertheless, values remain off course, the Bluetooth being around 10 % above the BRP. In all, the gap between $T_{BTH}(p = 50)$ and $T_{BRP}(p = 50)$ evolves in a $\left[-20\ \%, +20\ \%\right]$ interval, with a global 24-hour gap of 15 %.

When considering the dispersion of values around the median per t_{03min} time slots, it is striking to see that the BRP is absolutely not relevant. The IQR of the Bluetooth travel-time is 162 % over that of the BRP.

To conclude on the comparison between the two indicators, the median BRP travel-time $T_{BRP}(p = 50)$ can be considered "acceptable" when compared with the median Bluetooth travel-time $T_{BTH}(p = 50)$, as for example when analyzing a decade of traffic conditions, for which only BRP data is available prior to the Bluetooth beacons' setup. T_{BRP} gives for daytime, with sufficient levels of traffic, an "acceptable approximation" of the travel-time trends. Nevertheless, when considered on "free-flowing" periods, T_{BRP} clearly is offtrack, but this can be compensated somehow by the assumption that free-flowing traffic conditions haven't changed too much throughout the period of analysis.

When considering travel-time reliability, the BRP is clearly not the adequate tool: the dis-

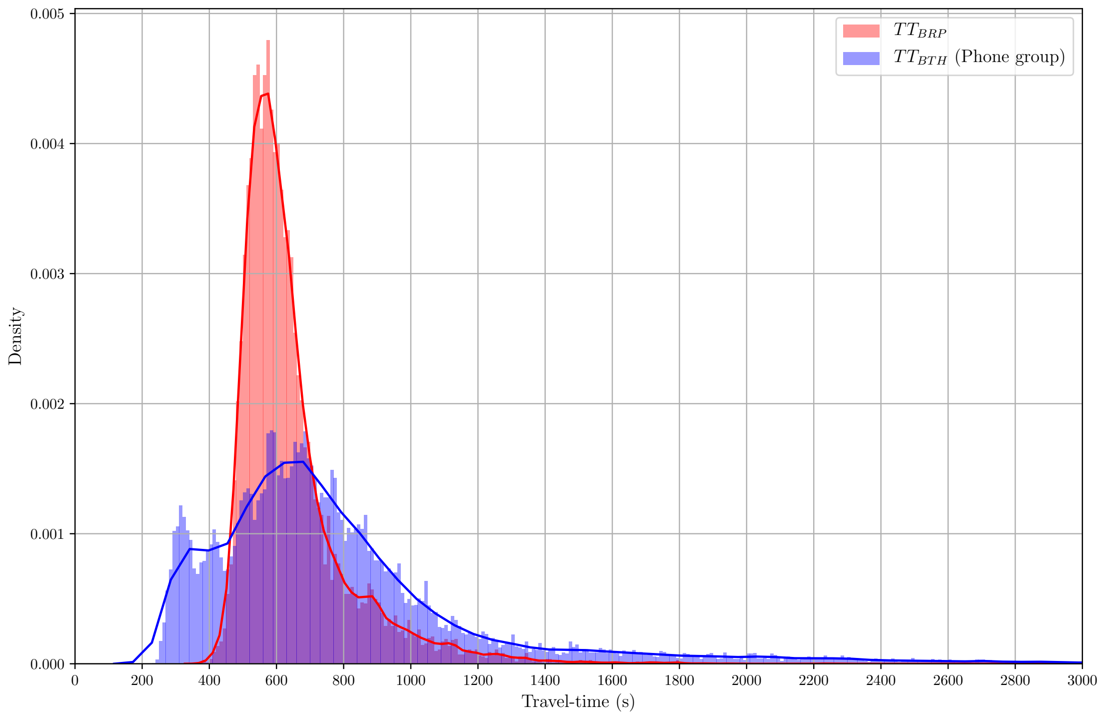

Figure 5.17 – St Germain, business days from March 15th to April 15th, 2016. Compared empirical distributions of Bluetooth and BRP (computed per 3-min slot) travel-times.

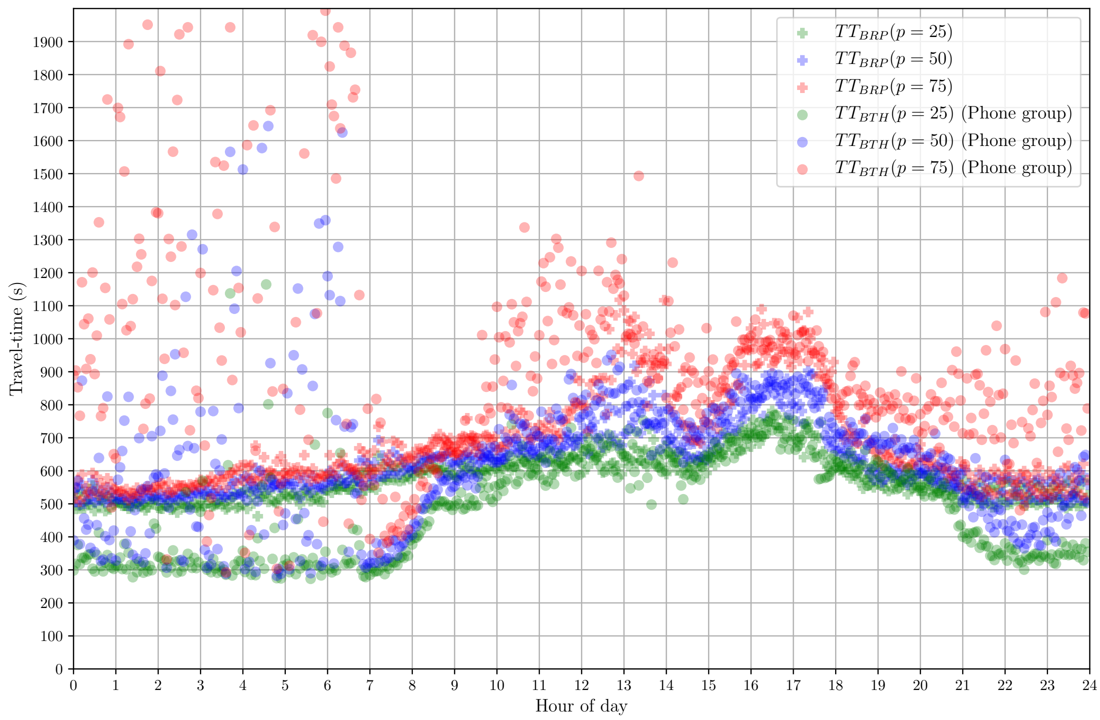

Figure 5.18 – St Germain, business days from March 15th to April 15th, 2016. Travel-time 25th, 50th and 75th percentile per t_{03min} interval for BRP and Bluetooth.

persion of values it yields is wrong. Note also that T_{BRP} is the result of an average of values (and the loops data itself is an average), whereas Bluetooth travel-times are individual journeys records. Therefore, the notion of travel-time reliability is better approximated by the Bluetooth travel-time T_{BTH} that by the BRP travel-time T_{BRP}.

5.6 Comparing the travel-times: operational conclusions on the operation

The expressway closed in July 2016, whereas the Bluetooth beacons had been collecting travel-time data since January 2016.

The before-after comparison of the travel-time on the two city center routes that constitute the most direct bypasses of the closed expressway section, the QHRD on the Right Bank, and the Boulevard Saint-Germain on the Left Bank, was the core of the experiment. The four beacons had been deployed six months ahead of the expressway's closure. These travel-times were also looked upon with great political scrutiny, as one of the chief arguments of the closure's opponents was that it would completely jam the city center.

The reference period, before the expressway closure, was defined over the business days from March 15th to April 15th, 2016. The travel-time collected during this period is known as the reference travel-time.

The after-the-closure period spans over the five months that followed August 2016, after Summer break, that is to say business days from September 2016 to January 2017 included. The period spans over several months on purpose, as to include the variations of the first weeks and the ensuing phase of stabilization of the routing strategies.

For each route, in line with the methodology in place, the comparison is done through the Bluetooth travel-time distributions and time-series.

Additionally, the travel-time trends are followed during the months that follow the closure. Politically it is important to know whether the situation is worsening, stabilized or improving on the two main diversion routes. Operationally, besides these political considerations, travel-time trends are a relevant input in estimating new routing strategies of drivers.

5.6.1 The Right Bank

5.6.1.1 Travel-times comparisons

For the Right Bank, both travel-time series are compared at the origin-destination level, regardless of the possible routes. In other words, the reference travel-time covers the two parallel routes, QHRD and VGP routes, whereas the travel-time after the closure, only covers the QHRD route.

Moreover, in line with previous sections, the distinction in the equipment population is made between the Phone and Headset groups. The assumption that the Headset represents motorized two-wheelers, as the plots and analysis show, still holds.

Figure 5.19 shows the empirical distribution of travel-time values over the same classes, and Table 5.3 shows the associated 24-hour aggregated statistics. Both Headset (two-wheelers) and Phone (general traffic) groups had reliable travel-times, with a unimodal distribution of the values, close to their respective median (low dispersion): for the Phone group, the median travel-time is 256 s for an IQR of 67 s; for the Headset group, the median travel-time is 318 s for an IQR of 87 s.

After the closure, the travel-time and its variability increase for both groups. The Headset group still travels faster (median travel-time of 536 s) than the Phone group (median travel-time of 745 s), with a more reliable (less scattered) travel-time (IQR at 387 s for the Headset, against

period name	group name	T_{BTH} count	$T_{BTH}(p = 25)$	$T_{BTH}(p = 50)$	$T_{BTH}(p = 75)$	IQR
2016REF	Headset	4,000	229	256	296	67
2016REF	Phone	42,532	283	318	370	87
AFTER	Headset	10,160	412	536	799	387
AFTER	Phone	185,297	460	745	1,090	630

Table 5.3 – Concorde to Sully origin-destination. T_{BTH} aggregated statistics per period and groups of equipments.

an IQR of 630 s for the Phone). The Headset travel-time distribution only shows one mode followed by a long tail, whereas the Phone distribution shows two modes. When compared with the figures from before the closure, this is, for the Headset group a 110 %-increase of the median travel-time and an associated 477 %-increase for the IQR (the travel-time variability). Likewise, for the Phone group, the increases are worse: the median travel-time suffers a 134 %-increase, and its IQR (the travel-time variability) increases by 624 %.

As shown by the travel-time time-series plotted on Figure 5.20, the modality clearly depends solely on time, given there is, after the expressway's closure, only one route to complete the origin-destination.

Figure 5.20 shows the before and after median travel-time time series, for either the Phone and Headset groups.

Before the closure, the Concorde to Sully travel-time was very stable and reliable throughout the day.

For the Phone group, three sequences can be identified: a night-time (before 07:00, and then after 21:00) travel-time, a day-time (from 07:00 to 21:00, except between 17:00 and 18:00) travel-time, and an evening-peak (from 17:00 to 18:00) travel-time, the latter showing a substantial increase of the travel-time. The Headset group barely shows any change throughout the night and day, except that its median is more scattered than the Phone's: as described before, this may be explained by the lower population and the driving habits of the two-wheelers.

After the closure, the situation clearly worsens. At night, the median travel-time is slower by a 100 s (as the expressway is closed, this is now the free-flow travel-time of the surface route). After 07:00, the travel-time increases, and both Phone and Headset curves split up, while generally following the same trend, although the Headset shows an increased dispersion.

The Phone group travel-time, between 07:00 and 24:00, has four successive sequences. It reaches a first peak around 09:00, decreases slightly, and then increases again before noon, roughly staying constant, above the morning peak, between 12:00 and 14:00. After 14:00, the major travel-time peak begin, reaching its highest value between 17:00 and 18:00, and then decreasing until 22:00, to again peak between 23:00 and 24:00, and reaching free-flow conditions by 01:00. The Headset group follows the same trend, with slightly lower and more scattered values. Table 5.4 gives the associated figures.

Note the heavy increase of both the Headset and Phone groups populations between before and after the expressway's closure. Counter-intuitive at first sight, since the capacity decrease necessarily means less traffic on the origin-destination, this increase is explained by the positioning of the Sully beacon. Installed on a street-light pole of the Quai Henri IV, part of the QHRD route, and overlooking the expressway just before it entered a tunnel, it likely missed many of the equipments traveling on it at a reasonably fast speed.

period name	group name	sequence	TT count	TT p25	TT p50	TT p75	IQR
2016REF	Headset	00:00 to 07:00	197	213.0	245.0	283.0	70.0
2016REF	Headset	07:00 to 09:00	571	230.0	254.0	287.5	57.5
2016REF	Headset	09:00 to 14:00	1005	231.0	255.0	291.0	60.0
2016REF	Headset	14:00 to 17:00	601	234.0	261.0	308.0	74.0
2016REF	Headset	17:00 to 18:00	286	231.25	269.5	334.75	103.5
2016REF	Headset	18:00 to 21:00	1022	227.0	251.0	293.75	66.75
2016REF	Headset	21:00 to 24:00	318	225.0	256.0	295.75	70.75
2016REF	Phone	00:00 to 07:00	4489	235.0	259.0	284.0	49.0
2016REF	Phone	07:00 to 09:00	5486	283.0	311.0	349.0	66.0
2016REF	Phone	09:00 to 14:00	10255	291.0	318.0	350.0	59.0
2016REF	Phone	14:00 to 17:00	7748	300.0	334.0	392.0	92.0
2016REF	Phone	17:00 to 18:00	3418	321.0	417.0	721.75	400.75
2016REF	Phone	18:00 to 21:00	6952	300.0	336.0	412.0	112.0
2016REF	Phone	21:00 to 24:00	4184	271.0	289.0	325.0	54.0
AFTER	Headset	00:00 to 07:00	1258	304.25	340.0	378.0	73.75
AFTER	Headset	07:00 to 09:00	1429	406.0	464.0	560.0	154.0
AFTER	Headset	09:00 to 14:00	2510	447.0	548.5	791.75	344.75
AFTER	Headset	14:00 to 17:00	1325	603.0	843.0	1280.0	677.0
AFTER	Headset	17:00 to 18:00	480	722.75	1128.5	1693.75	971.0
AFTER	Headset	18:00 to 21:00	1950	535.25	675.0	983.25	448.0
AFTER	Headset	21:00 to 24:00	1208	358.0	423.0	534.25	176.25
AFTER	Phone	00:00 to 07:00	30629	324.0	358.0	392.0	68.0
AFTER	Phone	07:00 to 09:00	27291	452.5	583.0	745.0	292.5
AFTER	Phone	09:00 to 14:00	43466	668.0	812.0	971.0	303.0
AFTER	Phone	14:00 to 17:00	28604	959.0	1202.0	1523.0	564.0
AFTER	Phone	17:00 to 18:00	9278	1259.0	1568.0	1942.0	683.0
AFTER	Phone	18:00 to 21:00	24133	882.0	1157.0	1503.0	621.0
AFTER	Phone	21:00 to 24:00	21896	421.0	502.0	624.0	203.0

Table 5.4 – Concorde to Sully origin-destination. Median and IQR by group of equipment and underlying time sequences.

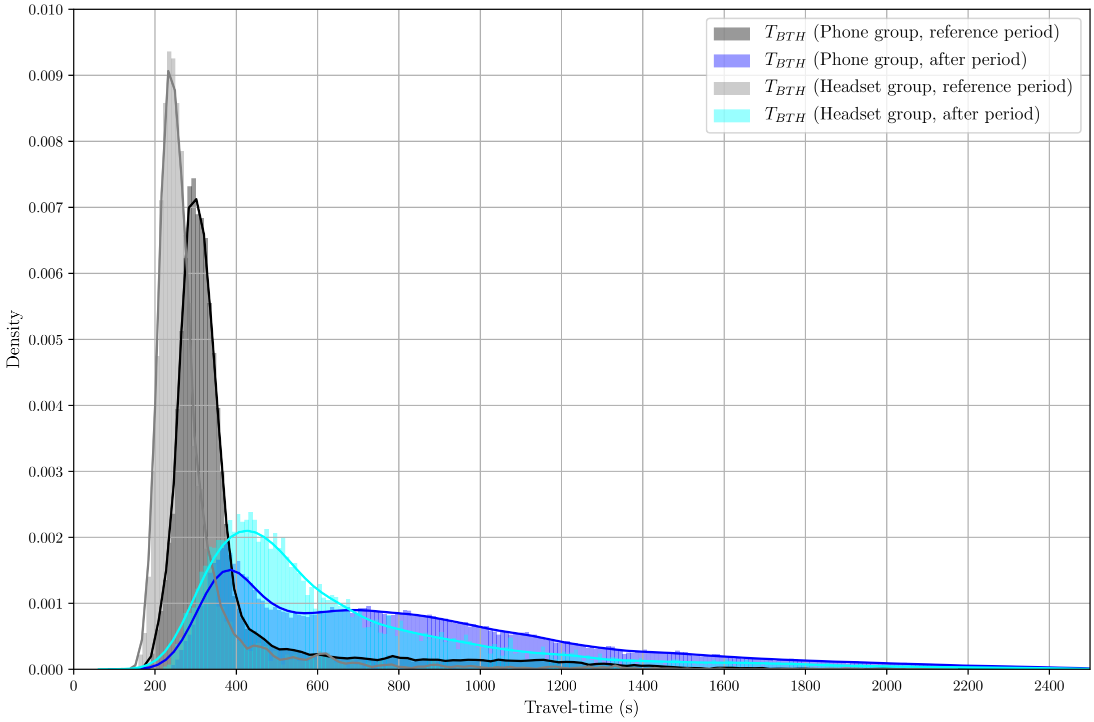

Figure 5.19 – Concorde to Sully origin-destination. Business days for the reference period (VGP and QHRD routes combined), compared with data from September 2016 to January 2017 (solely QHRD route). Empirical distributions of Bluetooth travel-time. Phone and Headset groups taken separately.

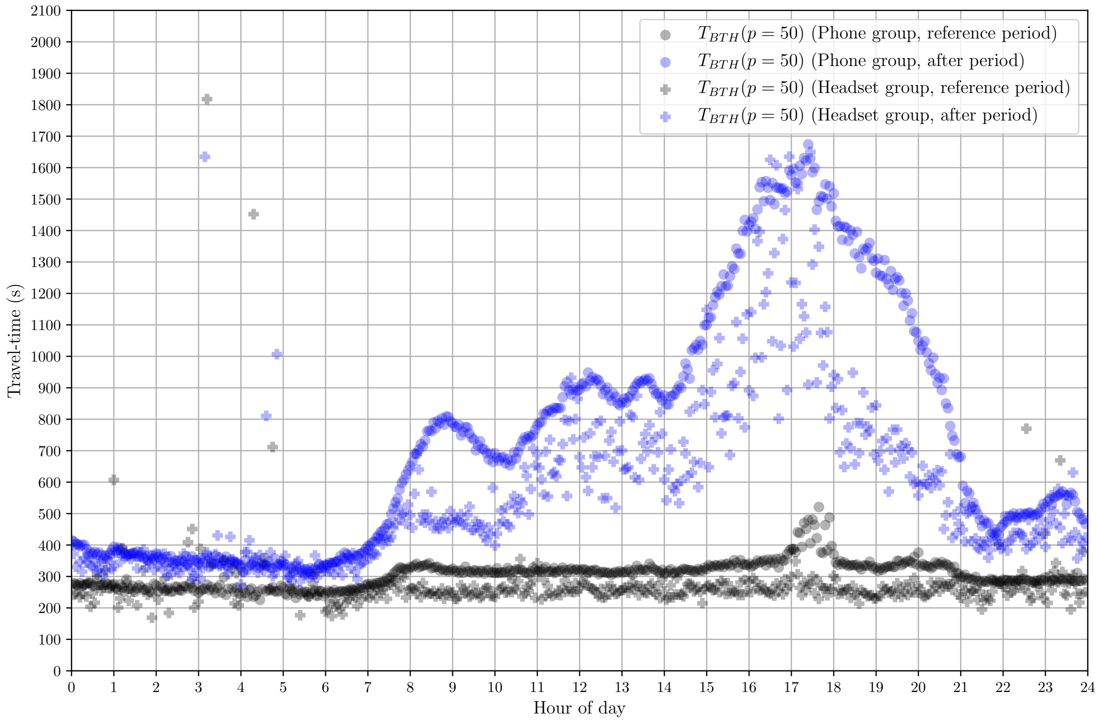

Figure 5.20 – Concorde to Sully, business days for the reference period (VGP and QHRD routes combined), compared with data from September 2016 to January 2017 (solely QHRD route). Time series of median Bluetooth travel-time. Phone and Headset groups taken separately.

5.6.1.2 Travel-times trends

Each median travel-time value is computed for each month, per t_{60min} interval, over business days. We consider September 2016, the first full month after the closure and the Summer vacations, as the post-closure reference period.

For these analysis, only the Phone group was taken into account.

Taking, on the Right Bank Concorde to Sully origin-destination, and for each hour of September 2016, the corresponding median travel-time as the index base 100 (first full month after the closure and Summer break), the other monthly travel-times are plotted on Figure 5.21. Over the five months considered, two periods can be observed. The first one, from October to November 2016, sees a sharp increase in travel-time relatively to September 2016, especially between 12:00 and 20:00. The hardest traffic conditions seem to be observed in November, with an increase in travel-time both in the morning, between 06:00 and 09:00, and in the afternoon and evening, between 12:00 until 19:00. December 2016 travel-times constitute the lowest of the five month, which can be explained by several days of alternate-day travel because of pollution, and the lower traffic between Christmas and New Year's Eve. January 2017 sees travel-time in the range of the December observations, except from 07:00 to 14:00 where the travel-times are close to the ones observed in September 2016. In the second half of the day, after 14:00, January 2017 travel-times are largely improved, with a decrease between 10 and 20 % between 18:00 and 22:00.

The monthly evolution of the travel-time distributions, shown by Figure 5.22, and the associated time-series, shown by Figure 5.23, confirms the observation made on the index base 100 time-series. For all months, the distributions are all bi-modal, with a first peak centered around 400 s corresponding to the free-flowing operation of the origin-destination, and the second peak, around 700 s, with a very long tail that ends at around 2500 s. Two groups emerge: the first three months, September, October and November 2016 on one side, and December 2016, January 2017 on the other side, with the first free-flowing peak higher than for the first three months.

It must be said that the observed variations, and the December 2016 and January 2017 improvements, questions the seasonal trends of traffic, which is hard to quantify. A longer observation of the traffic situation will say if the situation is "improving" six months and over after the closure. Nevertheless, these seasonal trends, aside December, can't alone explain the consequent variations observed between 2016 and January 2017.

5.6.2 The Left Bank

5.6.2.1 Travel-times comparisons

The second most-direct bypass of the central expressway section is, after the QHRD route on the Right Bank, the one-way Boulevard Saint Germain on the Left Bank.

Both for the reference and the post-closure period, the only route to travel the Assemblée to Jussieu origin-destination is the Boulevard Saint Germain.

The Boulevard Saint-Germain travel conditions before the expressway closure have already been presented, when qualifying the corridor free-flow speed based on travel-time observations.

The distribution of travel-times, plotted Figure 5.24, shows that the arterial has always had disturbed traffic conditions, as the travel-time distributions are not unimodal and quite scattered. Associated aggregated statistics are given by Table 5.5. The size of the two populations of equipments increases after the expressway's closure, in line with the traffic increase, by 800 % for the Headset group and by nearly 600 % for the Phone group. Note the Headset group population is very low for the reference period, and hinders any analysis of its distribution for that period.

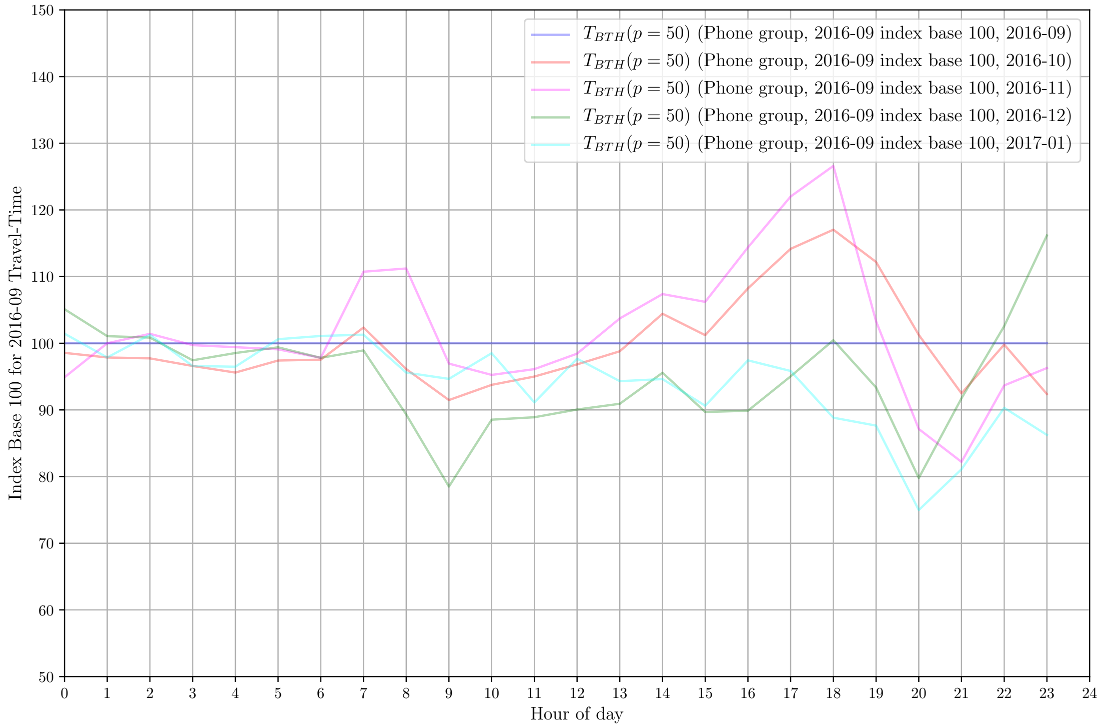

Figure 5.21 – Concorde to Sully, business days from September 2016 to January 2017 (solely QHRD route). Hourly median Bluetooth travel-time, computed by monthly periods. For each hour, the September 2016 median travel-time is taken as index base 100.

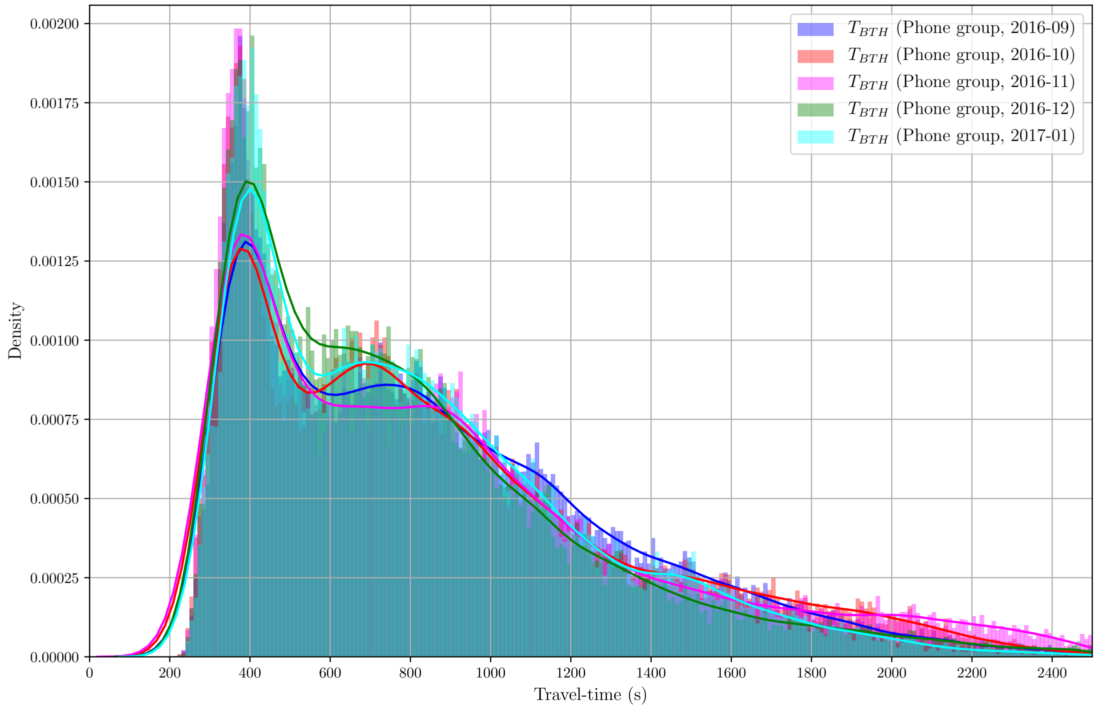

Figure 5.22 – Concorde to Sully, business days from September 2016 to January 2017 (solely QHRD route). Empirical distributions of Bluetooth travel-time.

For the reference period, the Phone travel-time shows two modes, with a dominant second mode (in which the median is at 692 s) and a reduced tail, the IQR being nonetheless quite long (381 s). After the closure, the travel-time increases increases slightly for the Phone group (from 692 s to

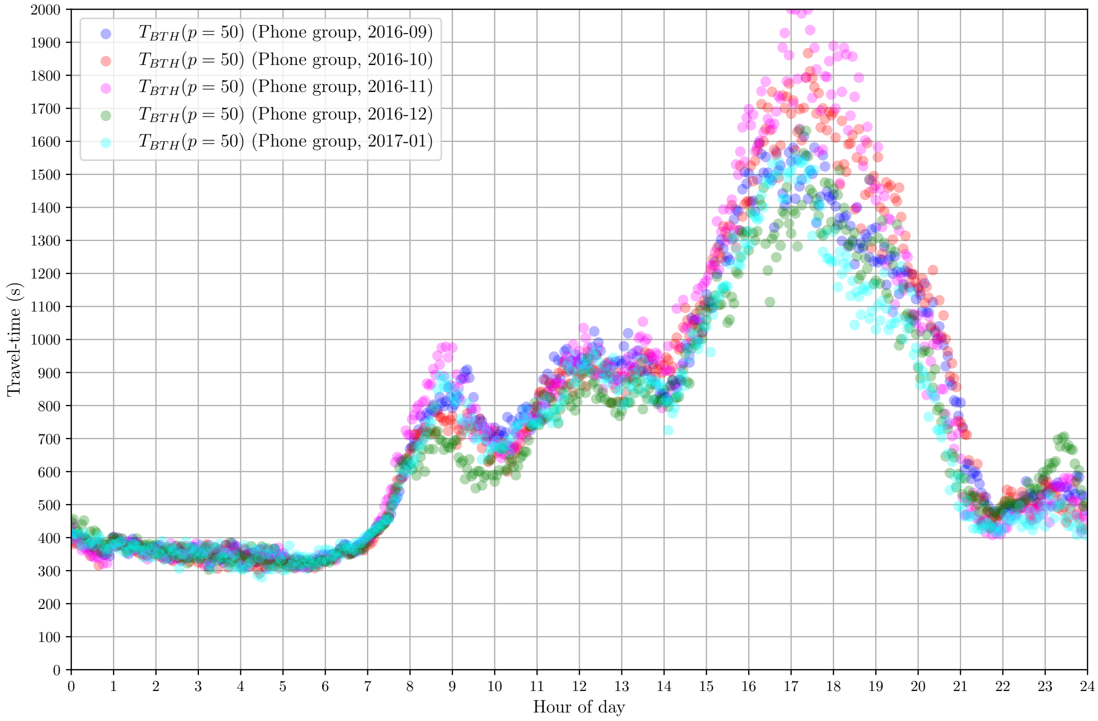

Figure 5.23 – Concorde to Sully, business days from September 2016 to January 2017 (solely QHRD route). Time-series of the median Bluetooth travel-time, computed per monthly periods and t_{03min} time-slots.

period name	group name	T_{BTH} count	$T_{BTH}(p = 25)$	$T_{BTH}(p = 50)$	$T_{BTH}(p = 75)$	IQR
2016REF	Headset	645	494	700	959	465
2016REF	Phone	21,751	528	692	909	381
AFTER	Headset	5,817	420	613	915	495
AFTER	Phone	150,916	499	717	979	480

Table 5.5 – Assemblée to Jussieu origin-destination. T_{BTH} aggregated statistics per period and groups of equipments.

717 s), and its variability worsens, as the IQR jumps to 480 s, a 25 % increase. The decrease in travel-time for the Headset group between the two periods has to be taken with care, given the very low population for the reference period.

Figure 5.25 shows the time series of the median travel-time for both the Headset and Phone groups, comparing the reference period and the five-month period following the closure. Before-after travel-times from 00:00 to 15:00 remain close. The only difference is a more marked morning peak around 09:00 after the closure. From 15:00 to 21:00, the travel-time has substantially increased.

The distribution and time-series analysis show that for the Phone group, the reference and after-closure distributions show two modes, with a strong dependency on time. The first mode is the free-flowing condition (morning and night), the second the daytime and evening traffic conditions. It is striking to see how the expressway closure has lowered the peak of second mode in the travel-time distribution, and redistributed the value before and after the peak, increasing the dispersion of values.

Table 5.6 gives the figure for both groups, along the following sequences: 00:00 to 07:00, 07:00 to 09:00, 09:00 to 15:00, 15:00 to 21:00, 21:00 to 24:00.

period name	group name	sequence	TT count	TT p25	TT p50	TT p75	IQR
2016REF	Headset	00:00 to 07:00	38	292.25	324.0	511.25	219.0
2016REF	Headset	07:00 to 09:00	56	309.75	440.0	608.25	298.5
2016REF	Headset	09:00 to 14:00	173	584.0	774.0	1208.0	624.0
2016REF	Headset	14:00 to 17:00	157	688.0	832.0	1063.0	375.0
2016REF	Headset	17:00 to 18:00	54	682.75	887.5	1160.0	477.25
2016REF	Headset	18:00 to 21:00	113	524.0	680.0	818.0	294.0
2016REF	Headset	21:00 to 24:00	54	297.0	367.0	460.75	163.75
2016REF	Phone	00:00 to 07:00	1955	312.0	489.0	1271.5	959.5
2016REF	Phone	07:00 to 09:00	1814	388.0	481.0	584.0	196.0
2016REF	Phone	09:00 to 14:00	5490	582.0	718.0	988.0	406.0
2016REF	Phone	14:00 to 17:00	4469	668.0	793.0	950.0	282.0
2016REF	Phone	17:00 to 18:00	1795	653.5	809.0	960.0	306.5
2016REF	Phone	18:00 to 21:00	3829	580.0	679.0	808.0	228.0
2016REF	Phone	21:00 to 24:00	2399	351.5	454.0	814.5	463.0
AFTER	Headset	00:00 to 07:00	355	273.0	305.0	417.0	144.0
AFTER	Headset	07:00 to 09:00	551	320.5	401.0	513.5	193.0
AFTER	Headset	09:00 to 14:00	1691	483.0	693.0	952.5	469.5
AFTER	Headset	14:00 to 17:00	982	612.25	836.0	1113.75	501.5
AFTER	Headset	17:00 to 18:00	410	633.75	902.0	1279.0	645.25
AFTER	Headset	18:00 to 21:00	1244	471.0	628.0	872.75	401.75
AFTER	Headset	21:00 to 24:00	584	301.75	374.0	456.0	154.25
AFTER	Phone	00:00 to 07:00	13559	295.0	336.0	646.0	351.0
AFTER	Phone	07:00 to 09:00	17635	384.0	498.0	641.0	257.0
AFTER	Phone	09:00 to 14:00	39656	609.0	767.0	957.0	348.0
AFTER	Phone	14:00 to 17:00	28113	725.0	909.0	1154.0	429.0
AFTER	Phone	17:00 to 18:00	9071	809.0	1078.0	1415.5	606.5
AFTER	Phone	18:00 to 21:00	24699	640.0	799.0	1060.0	420.0
AFTER	Phone	21:00 to 24:00	18183	350.0	413.0	545.0	195.0

Table 5.6 – Assemblée to Jussieu origin-destination. Median and IQR by group of equipment and underlying time sequences.

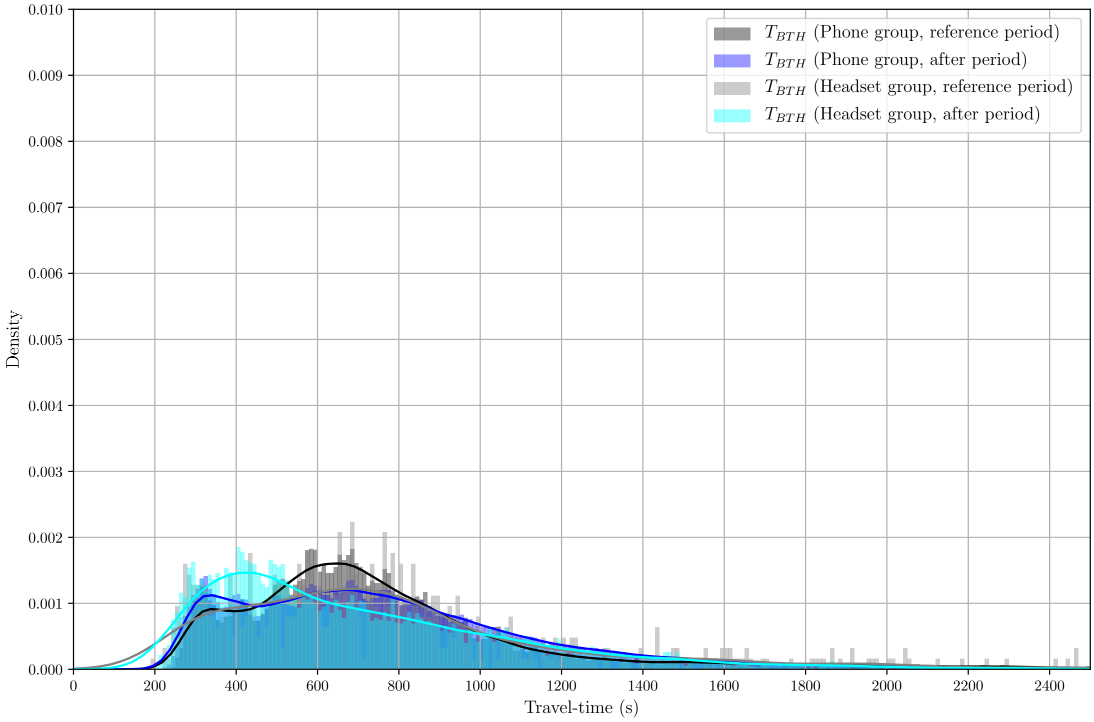

Figure 5.24 – Assemblée to Jussieu origin-destination. Business days for the reference period (VGP and QHRD routes combined), compared with data from September 2016 to January 2017 (solely QHRD route). Empirical distributions of Bluetooth travel-time. Phone and Headset groups taken separately.

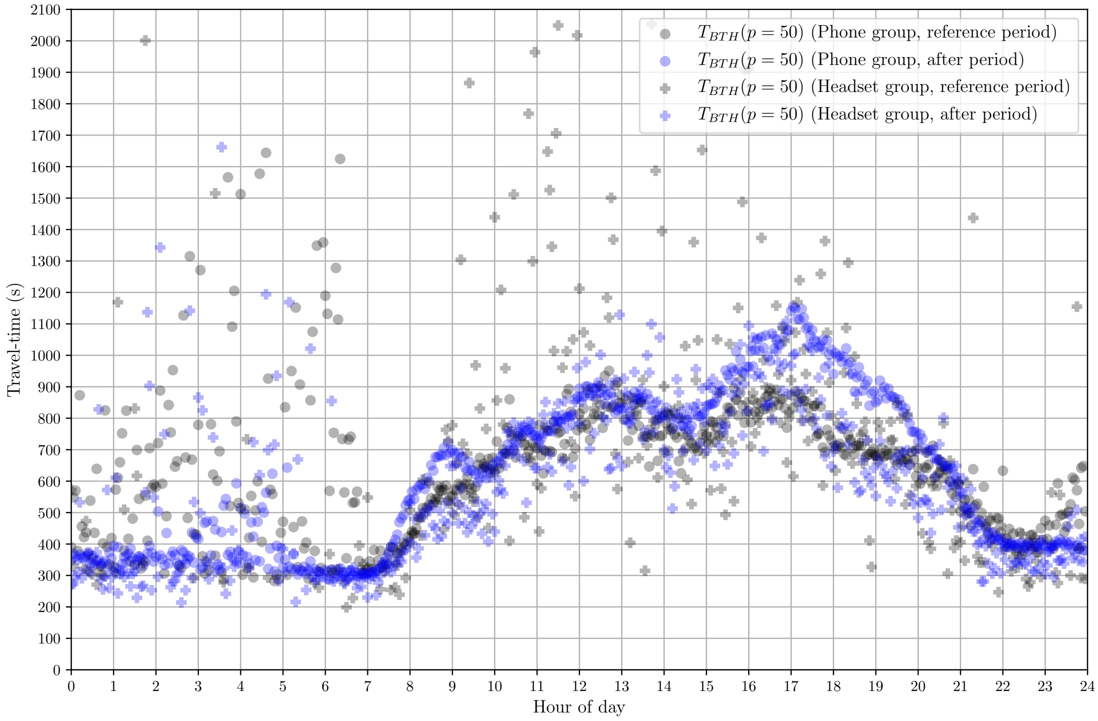

Figure 5.25 – Assemblée to Jussieu origin-destination. Business days for the reference period, compared with data from September 2016 to January 2017. Time series of Bluetooth median travel-time. Phone and Headset groups taken separately.

5.6.2.2 Travel-times trends

The analysis of the travel-times trends for the Assemblée to Jussieu origin-destination follows the same rules as the analysis done for the Right Bank QHRD route. Figure 5.26 shows the time series of the Bluetooth hourly median travel-times, with September 2016 data taken as index base 100. Due in part to the low number of records, data from 00:00 to 07:00 is highly scattered, which translates into suspicious median travel-time variations during these hours. We will therefore focus on the 07:00 to 24:00 period. As confirmed by the monthly empirical distribution shown Figure 5.27, the same two periods of months can be observed, like already done for the Right Bank: September to November 2016 on one hand, December 2016 and January 2017 on the other. The distribution of both periods is bi-modal, with a free-flowing peak centered around 350 s, and a second peak around 600 s followed by a long tail ending around 2500 s.

To conclude, the analysis of travel-time between the reference and the five month post-closure periods shows a strongly deteriorated travel-time for the QHRD route, since the operation implies suppressing a two-lane grade separated expressway paralleled by a signalized arterial road, which then constitutes the only route on the Concorde to Sully origin-destination. This is especially true in the late afternoon, from 15:00 to 21:00, as the West to East traffic movement is the strongest, people leaving the West and the city center for home outside the city in the East. The travel-time deterioration first translates in the dramatic increase of the median travel-time (or considering any other ranking statistics series above the median), as shown by the time series. The second aspect of the travel-time deterioration is the greatly increased dispersion of values, meaning that the reliability of the level of service on the corridor has been significantly worsened.

On the Left Bank, the Boulevard Saint-Germain case is "less" striking, as the signalized arterial just takes additional traffic diverted off the expressway. The increase in travel-time, true especially in late afternoon, between 15:00 and 21:00, gives an interesting insight on the *residual capacity* the Boulevard had. In other words, this is how much more traffic this already traveled signalized arterial is able to cope with, showing a significant drop in performance (travel-time). The said residual is seen here as a stochastic variable, the difference between the observed travel-time before and after the closure.

On both cases, the travel-times trends over a relatively short 5-month period seem more to speak of the seasonal variations of traffic than a possible change of routing strategies by the users. Despite the worsened traffic conditions, there is still a demand that makes use of all available capacity on diversion routes, even with congested traffic conditions.

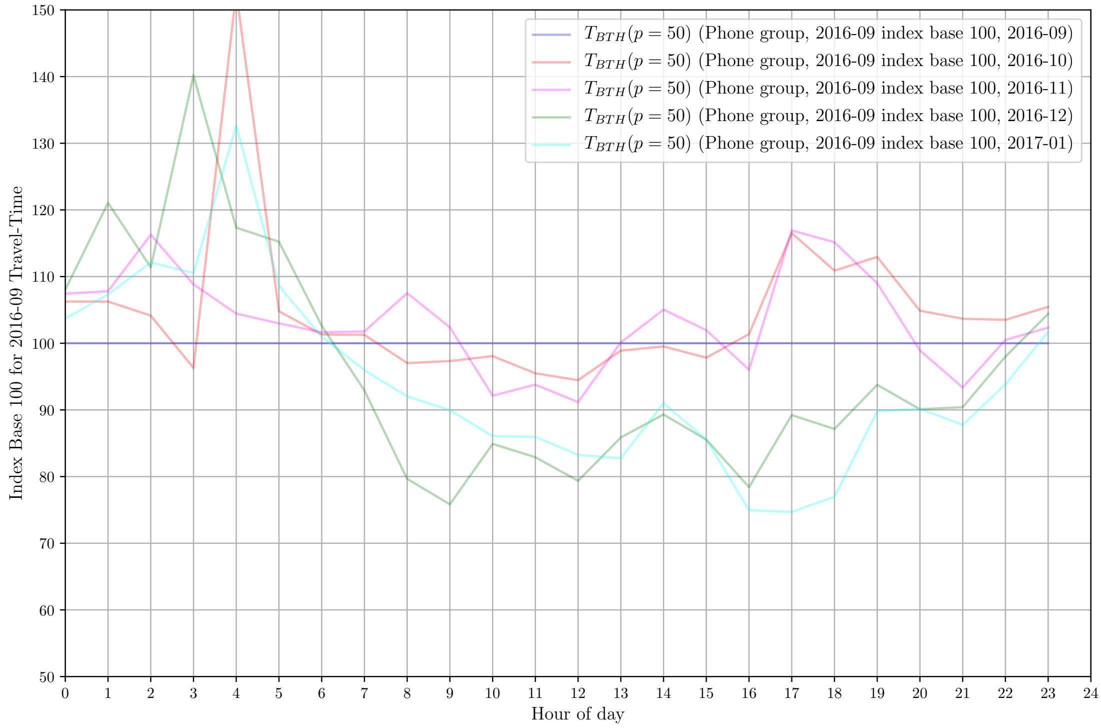

Figure 5.26 – Assemblée to Jussieu, business days from September 2016 to January 2017. Hourly median Bluetooth travel-time, computed by monthly periods. For each hour, the September 2016 median travel-time is taken as index base 100.

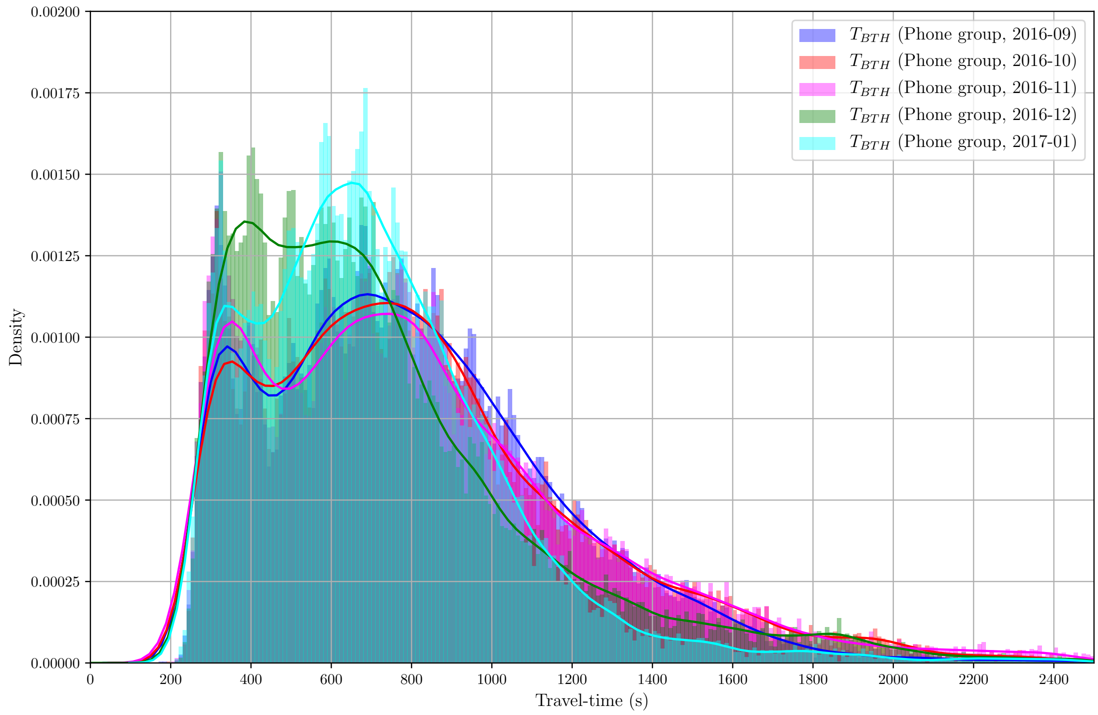

Figure 5.27 – Assemblée to Jussieu, business days from September 2016 to January 2017. Empirical distributions of Bluetooth travel-time.

5.7 Conclusion

The closure of the Right Bank Expressway, or Voie Georges Pompidou, between the Place de la Concorde and the Voie Mazas, caused intensive political turmoil, and made the assessment of the "experimental" closure even more sensitive. Bluetooth beacons, already experimented for the Place de l'Etoile tunnel's closure in 2014-2015, became a key data provider, through the travel-time they collect, for one of Paris biggest traffic-related decisions of the early XXIth century.

The use of the Bluetooth beacons for assessing origin-destination pairs across some of the heavily-trafficked arterials of central Paris allowed both operational conclusions regarding the expressway's closure, but also gave additional background on the use of Bluetooth travel-times.

Bluetooth travel-times offer an user-perspective to the Traffic Management Center: the travel-times distributions are drawn from individual equipment's travel-times, and not from averages such as the traffic loops data. These distributions yield two key informations: central tendency, such as the median or mean travel-times, traditionally used to summarize situations, but also the spread of the values around these tendencies. Quantifying the spread is a direct measurement of the variability of the travel-time, i.e. of the reliability of the route for the user. As a direct consequence, if the average travel-time was to broadcasted to the user, distributions of individual travel-times such as the one yielded by the Bluetooth beacons gives the user the probability he has to encounter such travel-time.

The direct comparison of travel-times distributions yielded the awaited operational conclusions regarding the traffic-impact of the expressway's closure: highly increasing travel-times, and a decreasing reliability of the diversion routes, as the spread of travel-times values increased.

Bluetooth travel-times also allow, given a careful analysis, to discriminate competing routes over the same origin-destination.

Results obtained from the Place de l'Etoile study were also confirmed, regarding the split of the equipments population into two major groups, namely the Headset group, accounting for motorized two-wheelers, and the Phone group, accounting for more general traffic. Of course, other users categories, such as public transit (passengers of buses) were not considered in the Author's approach. He believes the subject is more in the hands of the companies providing the Bluetooth beacons, who have access to additional informal such as the signal's intensity of each Bluetooth-enabled equipment within the detection range. The instantaneous detection of multiple devices could hint the passage of a bus near a beacon. Nonetheless, this option was ruled out for the Berges experiment, as the beacons were quite far apart and it was believed the number of equipments actually traveling the few bus lines that traveled the studied origin-destinations would be very limited.

Observed travel-times trends throughout several months periods seem more to speak of the seasonal variations of traffic than a possible change of routing strategies by the users. Despite the worsened traffic conditions, there is still a demand that makes use of all available capacity on diversion routes, even with congested traffic conditions.

In the end, three factors influence the shape of the Bluetooth travel-time distribution over an origin-destination:

- the traffic demand, whose direct consequence is the strong time dependency of the travel-times;
- route choices: if there are several competing routes for a same origin-destination, this will be found in the global travel-times distribution;
- the population of equipments: different categories have different uses of the roads, and

hence different travel-times.

Chapter 6

GPS speed FCD: the story of two different providers

6.1 Introduction

An increasing part of the global vehicle fleet is equipped with GPS receivers, being either dedicated terminals or embedded into other devices such as smartphones. Each receiver is generally linked to a private company providing traffic information and routing services through it. In return, each receiver transmits, among other data, their coordinates and speed to the service provider. This data is then stored onto servers, and used to provide the aforementioned traffic information services. The collection of this data over road networks makes up what is called "GPS-based Floating Car Data", shortened into "Floating Car Data", or "FCD". It might also be called "GPS probe data" or "probe data".

Most commercial GPS receivers transmit their data at low frequency: this is often referred to as "sparsely sampled probe data".

As of 2017, GPS-based Floating Car Data (GPS FCD) has been investigated in academic research since the 1990s. Traffic authorities have only begun to consider them as a serious source of traffic data in the late 2000s, at least in France. Lyon is believed to be the first city in France to seriously implement the use of real-time FCD data for traffic management through its Optimod'Lyon experimental program in 2012.

The main argument against the GPS FCD before 2012 and Lyon's program was its low penetration rate, whereas infrastructure-based sensors, mostly inductive loops, measure "all" the traffic that passes over them.

The work done in Lyon, and the published results, consolidated the credibility of this "new type of data".

Meanwhile, private providers began capitalizing, and communicating, on their work on GPS FCD applications: real-time traffic information and management, and offline studies using archived data.

At the PCE Lutèce, the Author began working on GPS FCD in 2013, solely on historical speed data, coming from sparsely sampled probe data. Real-time applications were not considered. In 2013–2017, the Author worked with data from two providers: a first one, referred to as "Provider 1" (P1), from 2014 to 2015, followed by a second one, referred to as "Provider 2" (P2), from 2016 onwards.

The purpose of this Chapter is to illustrate both the issues that arise when using new forms of data, but also the perspectives it opens on a better understanding of traffic dynamics in urban areas. It takes the stance of the PCE Lutèce, Paris arterials Traffic Management Center, showing how a TMC bought GPS FCD to carry out "offline" traffic studies, and what points were raised while analyzing the delivered data. The process ended up by elaborating some general guidelines to follow when dealing with such datasets. The issues found are often intimately linked to the studies undertaken. This Chapter focuses on the more technical, data-related aspects, leaving the operational studies results to Chapter 7.

The first section provides historical background on GPS FCD data, and its development as a tool to study traffic.

The second section focuses on the first tender of the PCE Lutèce, and deals with the issues faced with the dataset provided by Provider 1, and how these were solved.

The third section, from the lessons learned during the first tender, focuses on the second tender, and deals with the confrontation of the Provider 1 and Provider 2 datasets: how to ensure continuity and coherence of the data when different companies are at stake?

The chapter closes on a general guideline of good usage of the GPS FCD data for offline studies by a Traffic Management Center such as the PCE Lutèce.

6.2 Whereabouts of GPS FCD data

The first section provides historical background on GPS FCD data, and its development as a tool to study traffic.

It at first offers a historical background on the notion of "Floating car", already approached in Chapter 2, from manned observation to the GPS technology.

The section then shows some of the late 2000s milestones in research on GPS FCD-based traffic studies.

It then focuses on research works carried out on the issues faced with GPS FCD data by Traffic Management Centers that come not to depend solely from their traffic loops infrastructure: data available on the market can differ from the data available through purpose-built research infrastructure for experiments.

6.2.1 The floating car, an old idea

Among Floating Car Data, GPS-based FCD means that the GPS receiver aboard the vehicle elaborates data during the journey, and by extension the term GPS FCD mostly designates data generated by such devices.

In fact, the need to collect individual vehicle data can be felt very early in the traffic engineering literature. The technical limitations of the time, however, meant that such data could only be retrieved from roadside observation points or dedicated test cars.

In the 1920s, launching dedicated "floating cars" within general traffic seems to have gradually become a common practice, along with spot observations of traffic. For instance, in 1928, there are reports of a dedicated tool made for recording speed, and elapsed time and distance since the departure, of a "car floating with the traffic" [59].

The famous aerial campaign of the State Roads Commission of Maryland in 1927, is one of the earliest documented attempts to follow vehicle trajectories through "spot cars" ([17, pp. 106–108]) tracked from observers onboard the vehicles and onto the aerial views thanks to their intentionally white white roofs [17], as reported in Chapter 2. The purpose of these spot cars was to link their ground observations with the aerial ones.

Various techniques of sampling traffic with a test car running within it were developed. The main purpose served, as shown by Chapter 2, was always from the road authority's perspective: assess the performance of an arterial, a freeway, a network. The variable retrieved was journey speed (the space-mean speed) or journey time.

The "floating car" technique came to designate a very specific driving behavior: the test car was to pass as much vehicles as it got passed. Doing so, the speed at which the vehicle drives theoretically is the space-mean speed [46].

The question was always to find the best deal between data accuracy and cost, as running dedicated vehicles ended up being very expensive both in terms of time, material and personnel, both for the collection of the data, but also for its subsequent processing. In the early 1950s, under the patronage of the Highway Research Board, Berry and Green carried out extensive assessments campaigns of various "test car techniques" ([60, p. 311]) so that "a sampling technique whereby the speed of traffic on urban facilities can be measured on an annual basis with a reasonable degree of accuracy" ([60, p. 311]).

The energy question also brought up intensive research on estimating traffic patterns at the network's scale. In the 1970s, the chase-car technique was used by Chang and Herman [112] in several American cities to estimate, among other variables, "average speed [which] is particularly useful in measuring the 'quality' of traffic in different areas on various roadway types" ([112, p. 58]). The purpose was then to estimate the link between the so-called "traffic quality" and fuel consumption. The chase-car technique basically involved, within the area of study, randomly selecting and following a car and adopt the driving behavior of its driver, with an equipped test car that recorded, among other variables, the speed and acceleration.

The use of test cars fleet to time travel-times on selected routes is documented in Paris, from the 1950s and well onto the 1980s. The campaigns were ordered by the City of Paris as the road authority in charge of its network. They aimed at assessing the network's performance, facing the postwar rise of motor traffic, and backed the traffic planning scenarios that in turn triggered infrastructure planning.

In the 1980s, the inception of a city-wide sensors infrastructure, part of the Traffic Management Center, led to the demise of such manned campaigns in favor of estimating the journey speed through the loops data. Many other cities followed the same path through various technologies (automatic plate recognition, traffic loops, radars, etc.). Manned test-car runs became more scarce, and lost their importance. Instead of occasional measurement campaigns, the sensors infrastructure offered a real-time view of the equipped roads.

In the 1980s, besides traffic planning and management issues, the traffic information issue grew, as shown in the preceding Chapters.

This short historical perspective shows that the ideas behind today's use of the GPS FCD are not new: semantically, FCD has come to designate all forms of data collected from moving vehicles, which are known are probes. The decades-old ideas of feeding in traffic surveys for maintenance, planning and management of traffic can now be satisfied by a technology that was not available until the late 1980s.

6.2.2 The dawn of the GPS era: first assessments of GPS use aboard a vehicle

One of the first documented use of the GPS navigation system for land vehicles navigation is reported by a 1987 article, which describes the integration of an experimental GPS receiver onboard a Ford vehicle [113]. However, the GPS equipment remains rather complex and far from the compactness of today's devices, and that moment clearly not designed for widescale commercial deployment, as Figure 6.1 shows.

In the late 1980s and 1990s, research intensifies on the use of a GPS receivers to collect, in real-time, data regarding the dynamics and trajectory of the vehicle it is onboard of. Designing and experimenting systems based on probe vehicle data for traffic management and traffic incident detection is given serious thought in a variety of programs. A dedicated international conference, the "Vehicle Navigation and Information Systems Conference", is even held six times between 1989 and 1996.

The GPS system satellite coverage of the Earth became satisfactory in 1994, as from then on each spot on Earth was overlooked by at least three satellites 24 hours a day. At the time, one of the main downfall of the GPS accuracy was caused by the "selective availability policy", which deliberately introduced errors into the positioning delivered to civilians. The selective availability was only turned off in May 2000, and since then new GPS satellites do not include the equipment necessary to turn it back on: "While this action will not materially improve the performance of the system, it does reflect the United States' strong commitment to users by reinforcing that this global utility can be counted on to support peaceful civil applications around the globe." ([114])

Among the early 1990's studies, the work by ZITO, D'ESTE, and TAYLOR, carried out in South Australia, seems to be one of the earliest documented comprehensive studies [115] on the accuracy and usability of GPS location for traffic estimation and management purposes. The authors aimed at testing the accuracy of GPS location in an urban area (the test field was Adelaide Central Business District in Australia, characterized by high-rise buildings) and in the countryside, and its ability to deliver the speed of the GPS-equipped vehicle.

Their work considers GPS applications in traffic studies, reviewing the two ways a GPS receiver computes a speed, which can 1. either be derived from two successive locations, but that is error-prone as some locations can be erroneous; 2. or computed by the receiver itself, using Doppler shift from the signals it receives from the satellites in range. The study relied on one instrumented vehicle of the University of South Australia, therefore not a commercial equipment. GPS location and speed were logged into a computer, as were values of the car's speedometer, at a rate of 1 reading.s^{-1}. The authors therefore had access to raw GPS positioning and speed data, as computed in real-time by the receiver. Both speed measurements were then compared. Tests were carried out in the countryside, and in Adelaide CBD. The speed error vs. error relationship follows a normal law, even at a time when selective availability was still on. Results in the urban area were degraded, with a greater spread of speed errors, as satellite contact was sometimes lost by the receiver due to the "concrete canyons" ([115, p. 202]) created by the buildings. Nevertheless, the authors concluded that "although the GPS by itself may not be a 100 % reliable system, it is capable of providing an ongoing stream of position and speed data at a minimum frequency of observation likely to be useful for most traffic monitoring tasks." ([115, p. 203])

Another aspect of their study relates to travel-time measurements, with the combination of GPS data and a GIS software. The GPS data allowed, for a journey, to compute the moving time and stopped time. This recalls HERMAN and PRIGOGINE two-fluid model [116], although the authors make no mention of it. They nevertheless underline that "the amount of stopped time in a journey is an important performance indicator when assessing the efficiency of a road system and the level and extent of congestion." ([115, p. 206])

The study also mentions real-time applications for traffic data collection and traffic data broadcasting: the question of who is in charge of the information is asked, "how this information could be relayed would depend on the authority that had control over it" ([115, p. 207]), but public-based solutions seem to be the only one envisioned for the next years.

Zito, D'Este, and Taylor's work, at the dawn of commercial GPS positioning for cars, raised important issues: although the GPS precision has improved as the satellite fleet has grown and receivers have improved, it can still remain an issue in densely urbanized areas. The potential use of GPS data for network-wide analysis is well understood, especially regarding the stopped time indicator, already investigated through extensive test car runs since the 1950s. Finally, the authors were well aware of the future hurdles of the use of GPS data for traffic information, but the public-backed solution seemed to be, at the time, the only viable option.

In North America, the California PATH program[1], founded in 1986 by Caltrans and the University of California Berkeley, played in a leading role in the field, "navigation" then standing as one of its original three branches [117].

Among the reports of the PATH project, the 1995 report by Sanwal and Walrand, *Vehicles as Probes* [118], offers an early insight on the possible use of real-time probe vehicle data for estimation and prediction of traffic behavior as a "cost effective scheme" ([118, p. 2]). Sanwal and Walrand's work relies on the key assumption that "a vehicle traveling in traffic is a reasonable representative of the behavior of the traffic that it is part of, with some deviation that is statistical in nature". In other words, probe vehicle data vary stochastically from the collective data measured by loops (flow, speed). In the end, the same "collective data" as the one collected by the loops can be retrieved from probe vehicle data. Probe vehicle data is based on the GPS technology, and includes at least its position and speed. A base station, linked to the Traffic Management Center, is associated to each highway segment: data used by the TMC is link-based (link flow, link speed, link travel-time) and not vehicle-based, the base station carrying out the aggregation. The report formulates analytically the link speed estimation issue from probe vehicle data. An underlying assumption of computing link-based statistics is the homogeneity of flow among each link.

The usability of probe vehicle data is done by simulating a fleet of probe vehicles over a freeway, whose dynamics (flow and speed) are known from its loop detector data. Each freeway section bears a velocity profile as user input. A simulated probe vehicle follows a speed that is "obtained by a systematic perturbation from the mean speed for the location of the vehicle." The stochastic perturbation simplifies observations reported by Herman, Lam, and Prigogine more than twenty years before within their work on the kinetic theory of vehicular traffic [119].

Two cases are considered, interesting enough when related with the typology of commercial GPS data in 2017. They in fact correspond to two different sampling strategies of probe vehicle data. One is "time sampling": each probe independently reports its location and speed periodically. The other is "spatial sampling": each probe reports a travel-time once it has completed travel over a link.

A few downfalls to this early report must be highlighted: they show the change of philosophy that has occurred in the past twenty years. 1. The first downfall is the use of loop data as ground-truth, likely because proper technology was lacking to massively collect travel-times (like vehicle re-identification systems for toll collection) on the chosen segment of freeway. Today this is questionable, especially with the rise of re-identification systems such as Bluetooth-based systems that do not necessarily require heavy infrastructure. 2. The next downfall is the concept of a link base station, both meant to collect probe vehicle data and send back traffic information to the probe vehicles: this seems to assume the Traffic Management Center monopoly on traffic data collection and broadcasting, and a public infrastructure for all data exchange. History

[1]The "PATH" acronym originally stood for "Program on Advanced Technology for the Highway", and was subsequently changed, in 1992, to "Partners for Advanced Transit and Highways".

showed that this model more or less failed a few years after. 3. Finally, privacy concerns are not mentioned, although they were to become a major issue in the years that followed.

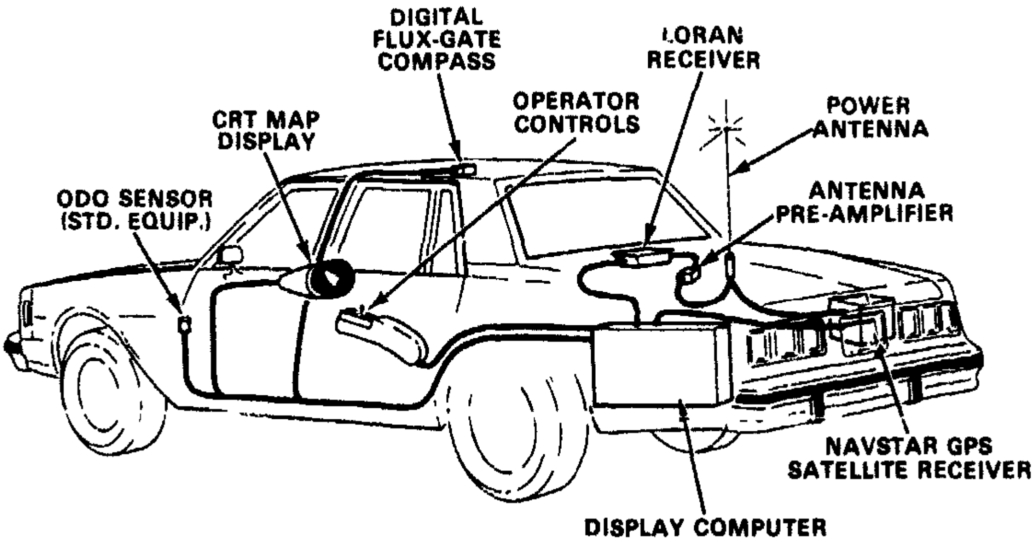

Figure 6.1 – 1987 GPS experiment. "Current navigation system functional component layout", reproduced from the paper by DORK *[113]*

6.2.3 Late 2000s production-ready experiments: the "Mobile Century" and "Mobile Millenium" Experiments

In the late 2000s, GPS-backed traffic studies made a major breakthrough, at least in terms of visibility and scale of deployment. Two experiments, "Mobile Century", followed by "Mobile Millenium", were held in California in the 2008-2009 period. Their aim was to experiment production-ready systems making use of various types of traffic data data, among which GPS FCD, while taking into account "side issues" like privacy.

6.2.3.1 A probe-vehicle based and privacy-aware Traffic Management Center: the "Mobile Century" experiment

The rise of GPS tracking technology and growing penetration rate also began to raise privacy concern. The "Mobile" experiments addressed it through the concept of "virtual trip line" (VTL) concept. The VTL [120] is a location-based sampling strategy of probe-vehicle data, designed to provide a "privacy-preserving traffic monitoring system" based on probe vehicle data. The main argument behind this strategy is that sampling through space instead of time increases privacy: "the rationale [...] is that in certain locations traffic information is more valuable and certain locations are more privacy-sensitive than others.". The authors also assume that traffic monitoring should rely "on aggregated statistics from a large number of probe vehicles", taken at a location, much in the spirit of legacy traffic loops infrastructure. As the authors define it, a *virtual trip line* is "a line in geographic space that, when crossed, triggers a client's location update to the traffic monitoring server.". It is defined by the set of values $[id, x_1, y_1, x_2, y_2, d]$, with id the trip line identifier, (x_i, y_i) the coordinates of the two endpoints, d the direction vector. The VTLs are defined by the traffic monitoring service provider on a specific server, and then updates the trip lines stored on the client side (the phone). Vehicles (the phones) only send an update when they cross a line they have in memory: they then send their position, the line ID, their speed, their direction of crossing the line. A VTL mimics the behavior of a fixed traffic sensor: measuring data at a specific location in space, and averaging it through time. Moreover, each VTL is associated to an area of influence, i.e. a road segment, as sensors are in a traditional traffic management system. The perspective remains that of the Traffic Management Center as the center of traffic management and traffic information, that has a hand on how traffic information is designed and broadcasted.

The VTL concept was tested in a controlled environment, with a fleet of 20 cars driven on a section of freeway, as an assessment of the proposed "privacy-preserving traffic monitoring system architecture". The route was divided into N sections, assumed to be between 50 and 100 ft long, on which it "[could] reasonably [be] assume[d] that speed is approximately constant along this short section." The VTL itself is associated with a link that can cover one or multiple consecutive sections. In the end, there are K links, with $K \leqslant N$. The VTL is in the middle of its link. The onboard devices were Nokia N95 phones, fitted with a full GPS receiver.

Focusing on the data aspect of the trial, mobile phones logged internally their position every 3 s. Speed information was computed using two successive location readings, and not retrieved from instantaneous speed measurement.

Like in previous experiments, the speed ground-truth was the cars' speedometers that were recorded: "on average, the vehicle odometer report a speed 3 mph slower than the GPS."

Location-wise, the GPS accuracy was confirmed, as frontage roads, which provide local access along the freeway corridor, could be differentiated from the freeway mainline: vehicles traveling on frontage roads where not identified as crossing VTL implemented on the freeway.

Regarding travel-time validation, "instantaneous travel-time" was computed, "which assumes traffic conditions remain unchanged on every link from the time the vehicle enters the link until it leaves the link", as the conditions on each link is given by the VTL reading (like it would by a fixed sensor: the methodology remains identical). "The travel-time of each link is computed with the length of a link and the mean speed that is obtained by averaging out speed readings from probe vehicles during an aggregation interval." The aggregation interval varies depending on traffic condition. The ground-truth was obtained a posteriori from the logged 3 s records. "The travel-time estimation generally improves with an increasing number of VTLs".

Finally, sampling intervals of the links were tested: "the general trend is that a longer sampling interval provides more accurate travel-time estimates. However, the RMS error increases again after 250 s, indicating that the aggregation interval should be shorter than the changing period of traffic conditions."

Capitalizing on the VTL beginnings, the February 2008 "Mobile Century" experiment appears to be one of the first proof of concept of a traffic monitoring system based on on-board devices and existing telecommunication infrastructures, but still within a controlled environment [54]. The system described not only bears a research aspect, but is clearly oriented towards production use.

The work highlights the cost of deploying and maintaining fixed traffic sensors. The experiment was carried out on a freeway section, and relied on a dedicated fleet of rented cars, driven following preplanned journeys, each being equipped with a GPS-fitted Nokia N95 phone that locally logged its position and speed every 3 s. GPS data was transmitted over the cellular network following the VTL concept.

The selected section of freeway already had loops that aggregate occupancy and flow data over 5 min periods. Two applications for the collected data are illustrated.

The first application was real-time, based on the VTLs, and aimed at drawing estimates of velocity and travel-times. A specific Kalman-filters based algorithm, previously defined, was used [121]. Qualitatively, the data drawn from the probes made a close match with the usual traffic information display on the Metropolitan Transportation Commission 511.org[2], which relies on loops, toll transponders and speed radars.

The (space-mean) speed ground-truth was a major issue, as this time cars' speedometers do not seem to have been used. Moreover, speedometers only give instant readings of the individual cars' speeds, but not of general traffic. Single loops detectors, which estimate speed from their occupancy and flow measurements, were ruled out as being error prone. Automatic number plate recognition (ANPR) systems were used to calibrate travel-times, and hence average speeds. Velocity fields were then integrated to compute travel-times (an a posteriori travel-time computation, called dynamic travel-time, or walk the speed matrix method). ANPR travel-time and VTL travel-times fell close, whereas single loops overestimated velocities. This underlines the fact that even a low proportion of equipped vehicles provides more accurate measurements than loops that measure all vehicles, the discrepancy being higher for lower velocities.

The authors deepened their analysis of the observed discrepancies between loop detectors and VTLs, by plotting the time series of both velocity measurements. It appears the gap is not constant, and levels of discrepancy varies with time, location, penetration rate and traffic conditions (reflected by the velocity). They raise the following bias:

- loop detectors bias;
- bias from test drivers, who for example got used to the route as they repeated their travel;
- both technologies have different ways of computing velocity and have different measurement errors. Loops derive lane speed from flow and occupancy measures, and then flow-weighted average over all lanes. VTLs obtain harmonic mean of individual GPS-computed velocity measurements.
- VTLs collect from data from a proportion of vehicles, whereas loops detectors gather data from all the vehicles. A too small proportion can yield statistical representativeness issues.

The second application was an offline analysis of the trajectories collected and logged by the mobile phones. This fed in the traffic model of shockwave propagation, by assuming a triangular relationship for the fundamental diagram, from which traditional traffic engineering parameters are inferred.

Velocity fields were computed by zone of influence, using Edie's generalized definition of speed [48], as the individual vehicle trajectories were known, and hence the aggregated distance traveled and the time spent on the said zone of influence. Once again there was qualitative agreement between the GPS-based and loop-based velocity fields.

Finally, throughout the experiment, consideration was given to the penetration rates of probe vehicles. The authors define the penetration rate as "the percentage of vehicles equipped vs. total number of vehicles on the road". During the experiment, the penetration changed over time and space.

The "Mobile Century" experiment was carried out much in the spirit of past experiments, within a controlled environment with a dedicated test cars fleet. Adopting the perspective of a Traffic Management Center that controlled the probe vehicle data process, through the VTL concept, it showed that a limited penetration rate of probe vehicle data could make up reliable fixed virtual sensors, much in the spirit of traffic loops, but providing reliable speed information.

The same philosophy would be continued with the "Mobile Millenium" experiment, this time in a wider area but still with purpose-built GPS-enabled phones.

[2] The Metropolitan Transportation Commission is the transportation planning, financing and coordinating agency for the nine-county San Francisco Bay Area.

6.2.3.2 The "Mobile Millenium" experiment: the proof of concept of a crowd-sourced Traffic Management Center

In line of the "Mobile Century", the "Mobile Millenium" experiment was launched, from November 2008 to November 2011 [122], this time with general public availability. The main objective remained to demonstrate the "the feasibility of traffic monitoring by using data from GPS-enabled cell phones [...] in an environment in which users were representative of the general public." ([122, p. 9]) A natural consequence of this was the demonstration that enough probe vehicles drove on the network to feed in public travel information services, complementing their existing fixed sensors infrastructure. Nokia and Navteq were the two main private sponsors associated with the program. French research was also involved, regarding the viability theory applied to traffic flow.

In its "Executive Summary" ([122, pp. ix–xi]), the *Mobile Millenium Final Report* underlines the market fragmentation regarding crowdsourced data, meaning that each company only has a small share of the global probe vehicle fleet. The report states that traffic information is only complete when its data sources hold "ubiquity, timeliness, accuracy, reliability" ([122, p. x]). This means that each "entity will most likely be forced to acquire data, or create data deals with other entities" ([122, p. x]). "Data feed fusion" ([122, p. x]) was then presented as the future of traffic data and traffic information infrastructures.

The project was, as its final report puts it, "the first 'participatory sensing' project ever for traffic estimation". The user-base of the Mobile Millenium experiment reached 5,000 users.

The various research works that resulted from the program's system mostly relied on VTL-based GPS data. Highway and arterial travel-time models were proposed, taking a hybrid approach with collected data and flow-modeling. Most relied on the triangular-shaped fundamental diagram, as it is part of "standard assumptions [made] in transportation engineering" ([122, p. 425]).

As stated before, the GPS data differs quite from the one that was commercially available to the PCE Lutèce. The real-time data available included both VTL-based collection and low-resolution individual points of the mobiles (i.e., sparsely sampled GPS FCD). The Nokia phones did not allow direct GPS-speed computations; instead, speed was inferred from a finite difference approximation was used (i.e. position based computation). Like Zito, D'Este, and Taylor's showed, such speed computation may not be as accurate was Doppler based speed computation.

The "Mobile" experiment also developed its own path inference algorithms (for the map-matching process) along with the mapping solution provider. This supposes access to the individual's vehicles data, or at least to GPS points, just as the program had.

Ground-truth for speed and travel-times for some of the experiments were expected to be derived from Bluetooth measurements, nevertheless these were set aside because they were "not accurate enough" ([122, p. 58]), although no further explanation is given.

From an user-perspective, the traffic information provided reused the "legacy" color-coded dynamic traffic map. The project raised the crucial aspect of a good representation of the data and models, in what is called the "model graph", simplified oriented graph representing the road network.

In the end, the "Mobile" projects raise the following issues. The first is that traffic management centers systems do not start from scratch, and their legacy framework has to be integrated, instead of being replaced, by the "new-coming" technologies. This was addressed for a part by the programs, nonetheless they assumed that the Traffic Management Center would keep control of all traffic information, without being bypassed by some of the actors.

The access to exhaustive GPS data, especially the positions themselves, is most often not possible for the TMC infrastructure. Some aggregation is already carried out upstream by the data providers, for various reasons that range from intellectual property to privacy policies. Moreover, the VTL-strategy is clearly impossible to implement: there is no way for a TMC to impose to private providers ways of computing their data. Most commercial receivers compute at a high frequency their speed and position, but only sends that information back to the provider's servers at a low frequency (like every 60 s). Moreover, trying to simulate fixed, spot-measurements made by traffic sensors with probe data kills off one of the major breakthrough of GPS data: the spatial sampling, whereas loops only sample through time. Finally, the probe data should be seen as distributions, and not only average values. Distributions bring forward much more information on the traffic state than simple averages, especially at a time where the user perspective is key.

6.2.4 The private market issue: a gap between research programs and commercially available data

Since the 2008-2009 "Mobile period", there has been a widening gap between the data available for these experiments, which relied on purpose-designed devices, and the data actually available on the market.

For a company that collects GPS probe vehicle data through an application or a receiver, there are two categories of commercial GPS data:

Commercial GPS receivers data, to which access may be granted for a research program;

Commercial GPS FCD data, which is sold to other entities such as a Traffic Management Center, often in aggregated form.

Academic research has begun, since the 2010, to investigate the commercial GPS data, although most studies concentrated on expressways.

6.2.4.1 Commercial GPS receivers data

As already mentioned during the "Mobile" experiments, one the main issue of GPS FCD data is the penetration rate. The penetration rate can be understood at two scales: the global fleet of GPS-equipped vehicles, and then the market share of each service provider within the global GPS fleet.

Patire et al. address this issue in a 2015 paper, "How much GPS data do we need?" [123], based on data collected in 2012. Their work is focused on freeways, and the travel-times estimates are drawn from data fusion, that include not only commercial GPS receivers data, but also loops-data and Bluetooth travel-times. Moreover, their procurement allowed them to access GPS point data. Among other observations, they concluded that, with the current penetration rates of GPS data on expressways: 1. "Unaggregated GPS point-speed data are proven to expand the coverage and accuracy of traveler information" ([123, p. 338]) through data-fusion; 2. "Probe data can be substituted for loop data for travel-time estimation" ([123, p. 339]).

In terms of data used, this study constrats with the VTL-approach of the "Mobile" experiments: the position now is not for the TMC to decide how probe data should be elaborated, but rather make use of existing commercial systems in which it does not have a direct hand. Nonetheless, the work is also a test for "data fusion engine" mixing several data feeds, and relies on GPS point data, which was not available for the PCE Lutèce to buy. Moreover, the computational load for a Traffic Management Center data-fusion engine that would collect, in real-time, all GPS points over its network would be very costly to maintain.

6.2.4.2 Commercial GPS FCD data

Research works that investigate commercial GPS FCD data tend to be rarer than works based on purpose-built data streams, that typically have access to GPS receivers data. Moreover, some investigations are carried out by the providers themselves!

Among the few independent studies that exist, Kim and Coifman's work [124], published in 2014, analyzed INRIX speed data upon a segment a freeway equipped with speed-measuring traffic loops which were due to be decommissioned (they were in 2011), the Traffic Management Center coming to rely only on probe vehicle data. The data covers two periods: a few months in 2011 with the two systems running side-by-side, and a few months in 2013 with only the INRIX speed.

The study relied on the freeway oriented graph model of INRIX: the data transmitted by INRIX was, for each link of the graph and every 60 s, the link id, the timestamp, the average speed, and two confidence indicators.

The conclusions of the Kim and Coifman's work, not only on the data but also on the context, underline the main issue of the relationship between private data providers and public Traffic Management Centers

The first point is assessing the INRIX average speed by comparing it with the loops speed. INRIX states that its data comes from "a variety of sources" ([124, p. 59]), meaning that "since the INRIX process is proprietary, there is no way to know if the INRIX data stream includes real time data collected by ODOT[3], i.e., the INRIX processing might include measurements from the same sensors that this study uses for evaluation." ([124, p. 62]) Keeping track of the traffic data feeds thus becomes extremely complicated, and some "loops" may even exist with algorithms feeding themselves with their own results...

The second point is regarding the coherence of the data. At aggregation intervals of t_{05min}, space-time diagrams of speeds from loops and INRIX were coherent, reporting similar traffic patterns (congestion, queue length, etc.). Nonetheless, when taking the shortest aggregation interval available, i.e. 60 s, discrepancies appeared: 1. INRIX data lagged the loop detector data by circa 6 min, an apparently already known phenomenon; 2. The t_{01min} refresh rate appeared somewhat artificial, as identical speeds were reported for several consecutive intervals for the same link: "this trend suggests that INRIX is effectively calculating the speeds over a longer period than it uses to report the speeds." ([124, p. 65]) The 2013 data showed an improvement, probably due to an increase of the INRIX fleet, and therefore more data was available to update more frequently the average speed. 3. Even the Confidence interval is proprietary, but it apparently did not account for repeated speed values.

When publishing their study, the authors warned that "given the competitive nature of the for profit traffic data providers, it is quite possible that in response to these finding INRIX and other data providers will start adding small random noise to their reported speeds to preclude such analysis in the future." ([124, p. 65]) This is a remainder of the difficulty for a Traffic Management Center to totally outsource traffic data and traffic information production, while at the same time aiming to control the reliability of the data. The TMC relies on traffic data, and this is a major challenge.

This section shows that the goals sought from probe vehicle data predate by far the inception of GPS-based FCD: early traffic engineers already experimented vehicles flowing with the traffic, fitted with equipments to record their path and speed. The purpose was to assess journey speed, or space-mean speed, and its reciprocal the travel-time. From the 1920s to today, it has

[3] Ohio Department of Transportation, the road authority in charge of the freeway segment studied.

been considered a key variable in assessing how a network performed, how well "supply" (the infrastructure) responded to the "demand", the resulting interaction being the traffic.

The rise of the GPS, and its widespread use, has somehow rendered test-car runs obsolete for non-academia purposes. It even means that Traffic Management Centers increasingly look upon the private market of probe vehicle data to gather traffic data, instead of maintaining a costly sensors infrastructure. This seems especially true for expressways, whose traffic dynamics are well-known. The TMCs did not even have a word in the way commercial GPS FCD data is produced, as shown by the VTL experiments of the late 2000s which originally aimed at providing a new infrastructure for probe-vehicle collection much in the spirit of traffic loops.

Assessing private GPS data, and especially commercial GPS FCD data, often aggregated at the scale of a road section (a "link"), remains an issue.

6.3 Tendering for GPS FCD: initial tender and first encountered issues (2014)

This section presents the work carried out on the Provider 1 datasets. It was the first encounter of the PCE Lutèce, an urban TMC, with probe vehicle data at this scale. At the time (2014), Lyon and then Paris were, to the Author's knowledge, the only cities in France to work on GPS FCD datasets at the scale of their networks, i.e. over several hundred of kilometers of road. At the same time, the DIRIF, the State Paris Region agency, was also starting to acquire data for its expressway network.

This tender offered an opportunity to define what the PCE Lutèce wanted: in order to avoid the technical complexity of a real-time data fusion structure, the path of offline data analysis was taken. Moreover, politics also played a role in launching the tender: speed-related decisions had been made, and the GPS FCD was seen (this view was shared among the PCE Lutèce's engineers) as a great tool to assess them.

The level of aggregation of the data chosen for the tender was decided as a compromise between privacy and proprietary issues (GPS point data was by no means available) and totally aggregated data (simple average speeds) that would be hard to assess.

At the outcome of the tendering process, a provider, referred to as Provider 1, was selected. After some preliminary work on defining a proper graph-oriented model for the road network, based on Paris traffic model network, a first dataset, referred to as "Provider 1 Dataset 1" (P1D1), could be delivered by September 2014.

The work on this dataset yielded several discoveries, and raised several issues, which are described in this section. This would not have been possible without the active cooperation of the Provider, who always answered the questions raised and helped circumvent the encountered issues.

6.3.1 GPS FCD: the process at stake

A floating car is historically a vehicle driving in general traffic and equipped with specific metrological devices, recording, for instance, its speed, its acceleration, the steering wheel or the wheels rotational speed, etc. Such vehicles have been used to record traffic patterns or conditions; in Paris travel-time measurement campaign with the help of such vehicles is documented since the 1950s [68]. In the literature, "proper ways" of driving such a car have been theorized, like the chase car technique [125, 112].

In a GPS-based floating car, all specific equipment resides mostly in two types of equipment: either a dedicated GPS terminal, or a smartphone running a proper traffic routing application. The whole range of these different equipments will generically be called "GPS receivers", or simply "receivers".

The receiver computes its position based on the broadcasted signal it receives from in-range GPS satellites. This position translates into the well-known latitude and longitude.

The receiver also computes its speed and heading. There are various techniques implemented, including the use of the Doppler shift.

These computations are done almost continuously by each receiver, and provide real-time information to the driver through the different receiver's outputs: screen, sound, etc.

A subset of the data continuously computed by the receiver is sent, at a given time frequency, by the receiver to the GPS service company servers over the cellular data network. This data, which will be referred to a "GPS raw record", is a record of values computed during the few seconds before the emission. This record generally includes at least the following attributes:

- the receiver unique identifier;
- the timestamp of the record computation;
- the position of the receiver at the time of computation (latitude and longitude);
- the heading of the receiver at the time of computation (in degrees);
- the instantaneous speed of the receiver (in km.h^{-1}).

The above list is not exhaustive, as the record can include acceleration, the steering wheel orientation, etc.

Each GPS raw record is therefore a punctual information (at the given coordinates). Each GPS raw record can also be called a "GPS FCD position" or "GPS point data".

There are generally two strategies for defining the process of emission of a GPS raw record (the receiver itself computes its position and speed more often than it sends data back to the company's servers). The first strategy is time-based: the receiver will emit its signal every δt, generally every one minute. The second strategy is event-based: each time an "event" occurs during the vehicle journey, a GPS raw record is generated and sent. An event can at first be inferred automatically from the receiver's computations: the vehicle stops, accelerates or slows down below or above a certain rate, changes direction (heading changes), travels a certain distance. An event can also be signaled manually by the driver, which allows a qualitative characterization of what's going on the road: accident, meteorological event (lack of visibility), etc.

The "GPS raw data" designates the set of GPS raw records received and stored by the provider.

The coordinates of each record then need to be matched with a model of the existing physical road-network. The model is a topological description of existing roads. Various models exist, produced by either GPS service providers or government bodies, including roads authorities. In such a description, the road network is represented as a graph, referred to as the "road network graph" or "network graph". A graph is characterized by its "nodes" and "edges". Physically, its nodes are intersections (with various levels of details given the scale at which the network is represented), and its edges, are the road sections. Therefore, a graph edge is abusively called "section" or "link" (as in "road section" or "road link") in a traffic context, and "section" and "link" will be considered synonyms of "edge". The graph can be or not "oriented", i.e. each way is represented by a section. If a two-way road links node A with node B, in a standard graph, there will be two nodes, A and B, and one section, AB. In an oriented, or directed graph, also called a digraph, there will still be two nodes, A and B, but two sections AB and BA, one for each direction of travel.

The process of matching GPS raw records to the model of the road network is called the "map-matching process". Various algorithms, either proprietary or open-source, exist to carry out the operation. In an operational context, given the volumes of data at stake and the complexity of the road networks, they require high computational power.

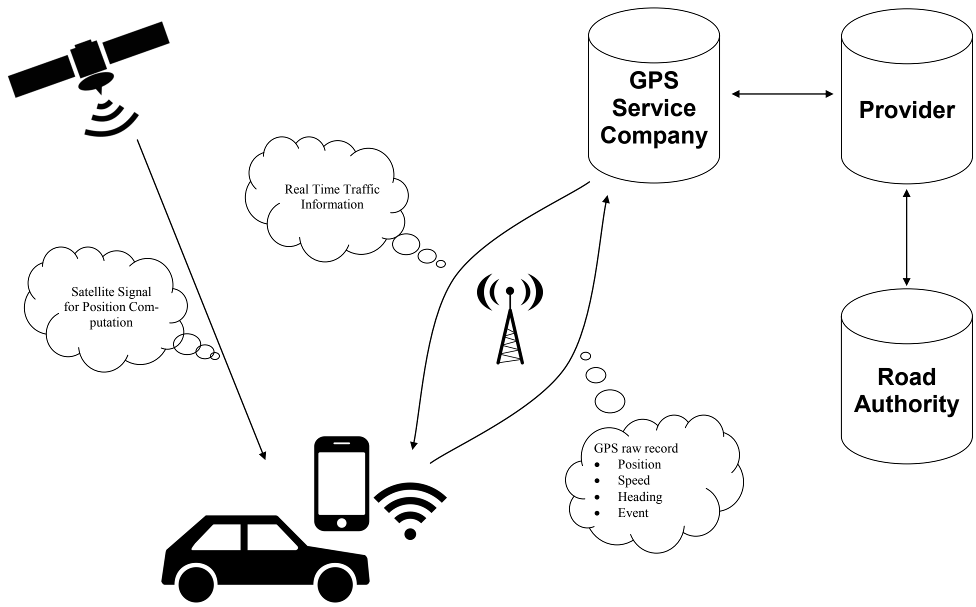

Figure 6.2 – Diagram of the GPS-based GPS FCD elaboration and broadcasting: from the vehicle, the satellite, to the GPS service company, intermediary providers, and road authorities.

6.3.2 The data available on the market

After the decision was made to experiment GPS FCD, the question that followed was to know the type of data that would be available for tender.

GPS raw data is not available for sale for various reasons. The first one is a privacy issue: possessing and trading such a sensitive database with millions of records of individual journeys, even if the receiver identification number is anonymized, is highly regulated. The second is that the private companies delivering real-time traffic information realize that they can make a business out of the archived data, selling traffic studies or data to public authorities or engineering firms. Another reason is the technical complexity of dealing with GPS raw data, and the computational power required, especially in the map-matching process.

Various company structures exist on the GPS market: in the case of the City of Paris tender, what will be referred to as the Provider is in fact an intermediary between the GPS receivers company and the road authority that buys the data.

The GPS receivers company behind the providers answering the tender, also known as the "GPS company" or the "GPS service provider", brands the receivers and provides the GPS real-time traffic service. Originally only based on dedicated branded receivers, it has also extended its user-base by launching smartphone applications. The information it retrieves is stored on servers, and used for real-time traffic information.

The GPS company can then sell directly either a direct access to its real-time feed (data coming from the receivers) and/or its historical data, with various degrees of aggregation, to other companies or road authorities. In fact GPS companies seem to be very often intertwined in complex conglomerates with various other third-party companies.

The Provider, as defined above in the case of the Paris tender, does not own the receivers fleet, but gets the GPS FCD from a GPS company with which it has contracted access to its real-time feed.

The City of Paris bought the GPS FCD data from such a Provider.

In 2014, other administrations that were on their way of or already purchasing data were mainly interested in having, per section of their road network graph, an average speed, refreshed with a given time frequency. In other word, an "average speed record" includes following attributes:

- s: the section identifier;
- t_1: the timestamp of the beginning of the time interval for which the computation is carried out;
- t_2: the timestamp of the end of the time interval for which the computation is carried out;
- $\overline{V}$: the average speed computed for the section s and the time interval ending at t.

Often the $t_2 - t_1$ difference is constant for a section, and is equal to the section's refresh rate. It must be chosen so as to gather enough data. In fact, not all cars are equipped with GPS receivers, and when tendering with a specific company, we will only get a fraction of the actual GPS fleet, meaning the penetration rate can quickly drop to just a few percents of general traffic.

The PCE Lutèce wanted more detailed data than just an average speed that is the result of successive proprietary algorithms over the GPS raw records. These algorithms often predated the public tenders of historical data, and were originally designed by the providers to give real-time travel-time and traffic conditions estimates to their users.

In the end, the tender enabled to get additional data than just the average speed per section and timestamp: the instantaneous speeds used to compute the average speed, and the number of cars at stake.

Within this first tender, the refresh rate of each section is based on the traffic volume of the road, as measured by the traffic sensors, or otherwise estimated through modeling. The covered road network was made up of 1400 km of the city's streets, including the ringway.

6.3.3 The first tender data structure

The data provided through the tender, for a section s and a timestamp t_2 (knowing the refresh rate associated with s, t_1 can be easily deduced) fell into three tables: one for the average speed data, one for the associated instantaneous speed values, and one for the number of unique receivers involved. Each line of a table is designated as a "record". t_2 is designated as the "section timestamp". The number of unique equipments involved can also be designated as the number of unique vehicles involved, as we can reasonably assume a one-to-one relationship between a vehicle and a receiver.

A relational database vocabulary, which also translates the actual computer implementation of the data, is adopted on purpose.

The "average speed table" has the following fields:

- s: section identifier;
- t: section timestamp;
- $\overline{V_{GPS}}(s,t)$: section average speed;

Category	Total length (km)	Estimated traffic levels (ADT by way)	Data refresh rate (min)
1	90	over 30,000	3
2	70	between 15,000 and 30,000	6
3	460	between 5,000 and 15,000	10
4	800	below 800	10

Table 6.1 – Sections of the first tender road network oriented graph: categories and associated cumulated lengths and average traffic levels.

- $\overline{T_{GPS}}(s,t)$: section average travel-time;
- $\sigma_{\overline{V_{GPS}}}$: standard deviation of the section average speed;
- $N_{GPS}(s,t)$: number of GPS FCD positions used in the computation.

The (s,t) pair of fields acts as the primary key of the average speed table.

The "instantaneous speed table" has the following fields:

- s: section identifier;
- t: section timestamp;
- V_{GPS}: instantaneous speed value, involved in the computation of the average speed.

The (s,t) pair of fields is a foreign key, referencing the primary key of the average speed table. If an average speed is computed out of several instantaneous speeds, each individual value will account for a record, i.e. there can be several rows bearing the same (s,t). Moreover, since for the same (s,t) couple, the same value of speed V_{GPS} can appear, and since that the individual receivers identifier is not present, the instantaneous speed table does not have a primary key.

The "unique identifier table" has the following fields:

- s: section identifier;
- t: section timestamp;
- $N_{id}(s,t)$: number of unique receiver identifiers, involved in the computation of the average speed.

Like for the average speed table, the (s,t) pair also acts as the primary key to the unique identifier table.

The first tender road network graph, an oriented graph, covered about 1400 km of the city's road network (counted as one-ways: a two-directional road counts twice, one for each direction). Its sections were split into four categories based on their estimated traffic levels, as shown by Table 6.1.

The traffic levels were estimated with the help of the traffic count stations (mostly for the roads that fall into the first and second category), and of the city's traffic model for the un-equipped streets (mostly for the third and fourth category).

Each category was then associated to a data refresh rate, under the assumption that the more vehicles there are, the more data there is on a small time scale.

In what follows, two main subnetworks will be considered: the "Tout-Paris-Intra-Muros" (TPIM) Network, which includes all main arterials of Paris, and the ringway.

6.3.4 Encountered issues

The first step in data exploration consists in plotting univariate empirical distributions of the variables: $\overline{V_{GPS}}(s,t)$, $V_{GPS}(s,t)$, $N_{GPS}(s,t)$ and $N_{id}(s,t)$. This allows to quickly grasp the datasets and their first physical and statistical properties (median values, dispersion, range, etc.).

The first data delivery of Provider 1, referred to as P1D1, was made between late 2014 and early 2015. The supplied P1D1 dataset included both average and instantaneous speeds tables.

Speed set	Count	25th p.	50th p.	75th p.	average	st. dev.	IQR
running	29,797,635	19	30	42	31	15	23
stopped	15,570,700	0	0	0	0	1	0
all	45,368,335	0	18	36	20	19	36

Table 6.2 – Descriptive statistics by mode of the instantaneous speed distribution of the first delivery of Provider 1, business days of October 2014.

The investigations that follow were carried out on various subsets of the instantaneous speed table, and have underlined several flaws: abnormally high values, multiple identical records.

6.3.5 The distribution of instantaneous speeds

For the analysis of univariate distributions of the variables at stake, average speeds were set aside, and focus was put on the instantaneous speed values $V_{GPS}(s,t)$. The latter constitutes the dataset closest to the GPS raw data.

The network considered here is the TPIM.

The speed values transmitted are integers, ranging from 0 to 130 $km.h^{-1}$. Figure 6.3 shows the instantaneous speed distribution over the TPIM network, for the business days of October 2014.

The first striking element is the bimodality of the distribution.

The first mode mainly consists in zero speeds, accounting for nearly 33 % of the total 45,368,335 records. This has a massive "scale-effect" on the second-mode of the distribution which appears flattened.

The second mode is made of strictly positive speeds, i.e. speed values starting at 1 $km.h^{-1}$, shown by the histogram on Figure 6.4. 1-speed holds nearly 1 % of the distribution values, and constitutes, along with values ranging from 2 to 5, the tail of the first mode. The second mode really begins at 5, and gradually increases to peak at 33 $km.h^{-1}$ (1.6 % of the records), and then decreases sharply (53 $km.h^{-1}$ stands at 0.05 % percent of the records), until peaking again at 54 (0.07 % of the records) and 55 $km.h^{-1}$ (0.015 % of the records). Past that value, the decrease resumes with the previous trend (56 accounts for 0.003 % of the records), and the long tail continues decreasing past 90 until 130 $km.h^{-1}$. At 130, the maximum value, there is a threshold effect, with a small peak (2,335 records).

From these observations, two modes can be identified:

- the "stopped mode" for $0 \leqslant V_{GPS} < 5$
- the "running mode" for $5 \leqslant V_{GPS} \leqslant 130$

Table 6.2 shows the associated aggregated statistics. The stopped mode has a median of 0 and an IQR of 0, whereas the running mode has a median of 30 and an IQR of 23. The overall distribution has a median of 18 and an IQR of 36. The weight of the stopped mode in the median speed of the network, and its dispersion, is extremely important.

The overall observation of the instantaneous speed distribution of P1D1 allows to assume a bimodality of GPS FCD speed distributions: a first mode, referred to as the "stopped mode", and a second mode, referred to as the "running mode". The terminology is directly inspired by Herman and Prigogine [116].

With these definitions, the distribution still showed suspicious peaks that remained to be explained. These will now be investigated.

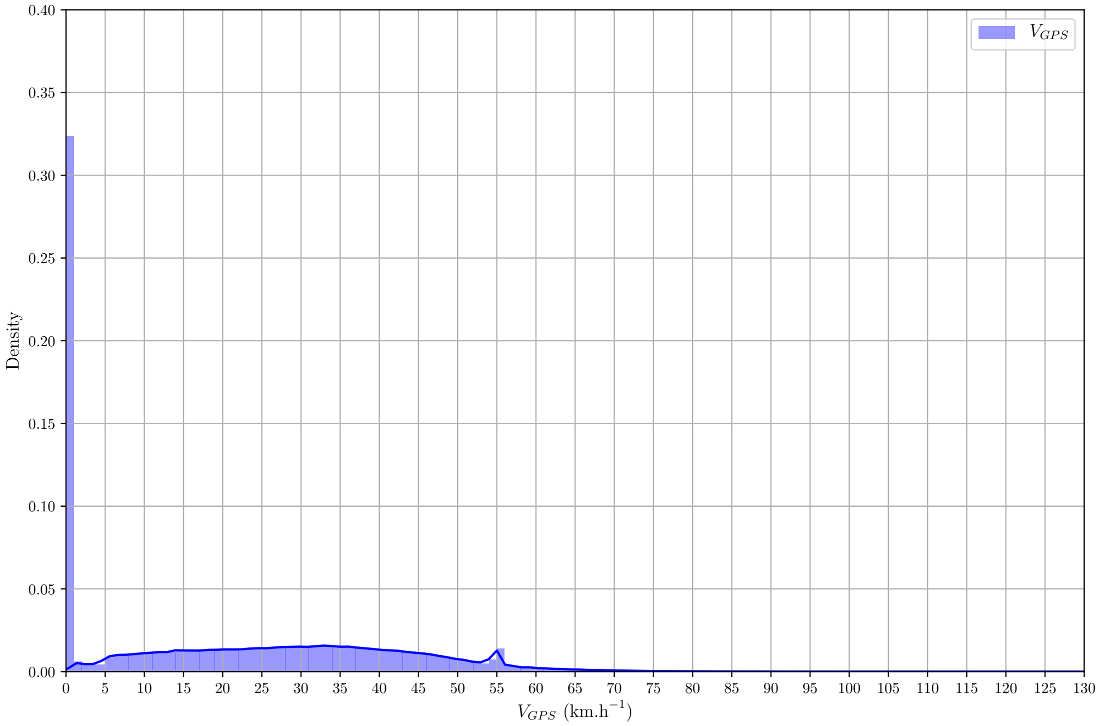

Figure 6.3 – Provider 1. First delivery. Distribution of instantaneous speeds V_{GPS}. Business days of October 2014.

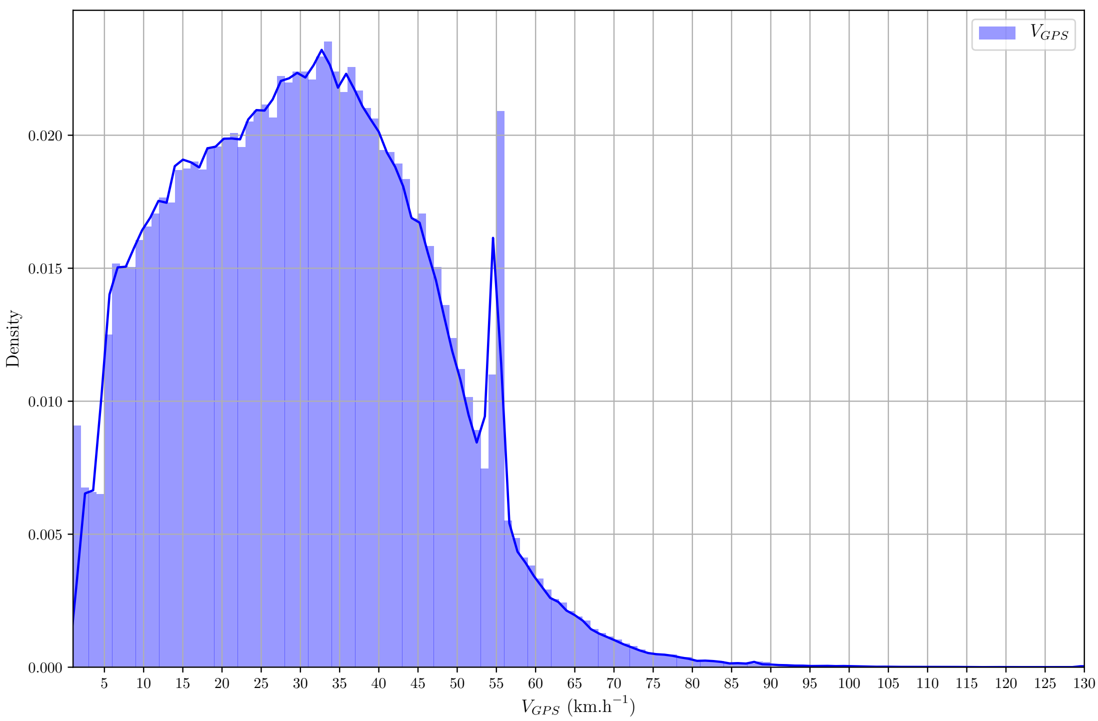

Figure 6.4 – Provider 1. First delivery. Distribution of instantaneous speeds V_{GPS} (values in]0;130]). Business days of October 2014.

6.3.6 Deterministic peaks

The general description of the instantaneous speed values has allowed to identify two modes: the stop mode, for speed values between 0 and 4, and the running mode, for speed values between

Speed set	Count	25th p.	50th p.	75th p.	average	st. dev.	IQR
running (original delivery)	29,797,635	19	30	42	31	15	23
running (with interpolation)	29,217,332	19	30	41	30	15	22
stopped	15,570,700	0	0	0	0	1	0
all (original delivery)	45,368,335	0	18	36	20	19	36
all (with interpolation)	44,788,032	0	18	35	20	19	35

Table 6.3 – Descriptive statistics by mode of the instantaneous speed distribution of the first delivery of Provider 1, with 54-55 speed first degree interpolation, compared with the original delivery, business days of October 2014.

5 and 130. The apparent physical regularity of the running mode is broken by two peaks that the Author assumed to be of deterministic source.

Two deterministic peaks within the distribution tail appear: the first one, the most striking, appears at speeds of 54 and 55 $km.h^{-1}$. The second is at the extremal value of 130.

The 130-peak can be easily explained. 130 is the highest legal speed in France. Therefore any GPS speed retrieved that was above 130 was seemingly truncated down to 130, hence the small peak. These make up only a very small number of records, but significant enough: for instance, 120 accounts for 95 records over the period, whereas 130 account for 2335 records. Moreover, the maximum legal speed in Paris is 50 in the inner city, and 70 on the ringway (lowered from 80 in January 2014). This peak was solved by eliminating the 130 value, and more generally speeds above 100 (two times the maximum speed limit on the TPIM network), all speeds above that threshold value accounting for 10,294 records, i.e. around 0.0002 % of the total number of records.

The second peak is a more tricky issue. Looking at their spatial distribution on the network, it appeared that most records holding these speed values were on sections s in the vicinity of tunnels, overpasses, underpasses. A discussion with the Provider, which himself turned to the receiver manufacturer, allowed to find an explanation: when a GPS receiver freezes for some reason, like loosing the satellite signal, it automatically freezes at a speed value of 110 %$\times$ the speed limit of the road it assumes to be on. A deterministic cause was behind the peak, which broke the "natural gaussian-like" decrease of the speed values past 33 km.h^{-1}.

The solution to this was to approximate the "physical" probability of having a 54 or 55-speed. The simplest method, given that only two values are impacted, is to use a local first-order polynomial (hence linear) approximation of the aberrant values, based on the nearest lower (53) and upper (56) speed values.

Another solution would be to use the Gaussian-kernel approximation of the running mode, which supposes each speed value is the expected value of a Gaussian law. The physical justification of such an assumption would have remained unclear, moreover it would have allowed negative speed values and introduced unnecessary computational complexity.

The resulting distribution is plotted on Figure 6.6, and its main descriptive statistics are given by Table 6.3, with respect to the two previously defined running and stopped mode. It shows the limited impact the peak has on the overall distribution statistics: the median, the 75th percentile and the IQR are lowered by 1 km.h^{-1}. The additional computations involved in the interpolation, given the impact of the peak on the overall description of the speed database, questions the interpolation's relevance in further analyses.

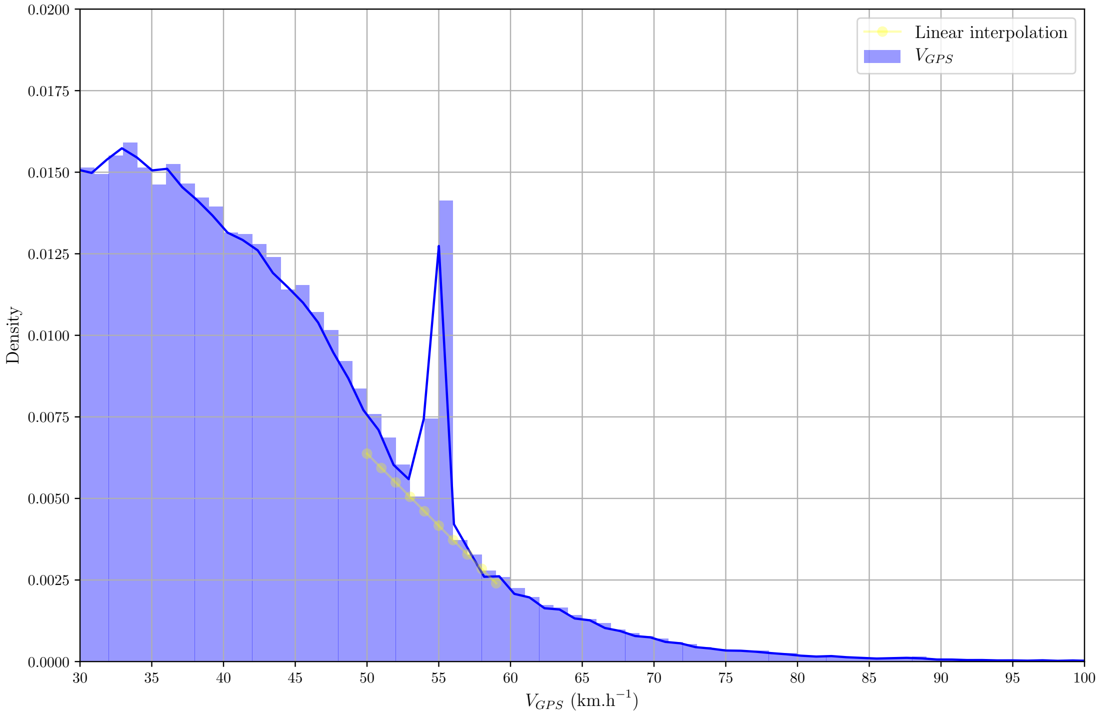

Figure 6.5 – Provider 1. First delivery. Distribution of instantaneous speeds V_{GPS} (zoom on values in [30;130]), with first degree interpolation for 54 and 55 values. Business days of October 2014.

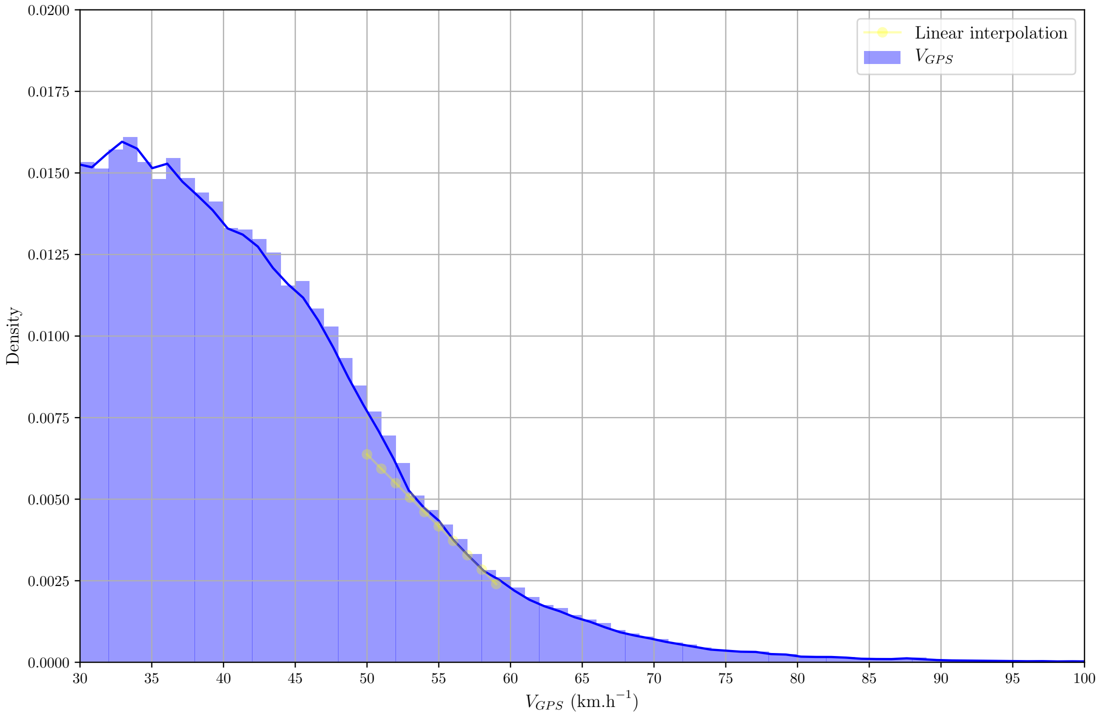

Figure 6.6 – Provider 1. First delivery. Distribution of instantaneous speeds V_{GPS} (zoom on values in [30;130]) with 54 and 55 interpolation. Business days of October 2014.

6.3.7 The time dependency of the number of GPS FCD positions

Each GPS raw record, i.e. each instantaneous speed record, is at least theoretically associated with a GPS position. This allows to derive a new variable related to the density of available information on a network: the number of GPS FCD positions, N_{GPS}.

N_{GPS}, as will be shown below, holds information on the traffic dynamics of the network, but also on the coverage of the network, through its associated linear density λ_{GPS}.

The provided data allows to compute N_{GPS} by section s and timestamp t: $N_{GPS}(s,t)$.

Most vehicles making up the Provider 1 dataset emit a GPS raw record on a time basis, every $\delta t = 60\ s$. This means that a vehicle i traveling at a speed v_i will cover a distance of $v_i \cdot \delta t$ between two GPS raw record emissions. For a section s of length L_s, the number of positions n_i a vehicle i will emit on it, for the timestamp t of the section, depends on:

- its speed v_i;
- the length L_s of the section;
- the duration of observation Δt_s (the refresh rate of the section).

The number of positions is an extensive quantity that can be summed through several sections.

Analytical developments will be carried out later on, nevertheless these first elements show how the "amount of GPS FCD information" collected on a specific road section depends on the traffic conditions (speed), the observation time frame and the section itself (its dimensions). Considering the section as a bounded area of (t, x) plane, the number of position $N_{GPS}(s,t)$ on it is function of the time and space boundaries $[t - \Delta t, t] \times [x_s, x_s + L_s]$.

The different refresh rates of the sections means makes the hour their least common denominator. The TPIM network is assumed that it remains a "closed network" on a per hour basis, i.e., assuming that everything happens "as if" no cars were leaving or entering the network during each hour. Another way to see it is that each car holds a unique label, and that whenever a car leaves the network, another car enters it and takes its label. This, at least for a part, solves the duration of observation bias (as a car will always be observed within the hour).

To understand how the number of GPS positions N_{GPS} accounts for the traffic dynamics on the TPIM network, Figure 6.7 plots its hourly boxplot distribution. The number of positions range from 40,000 positions in the middle of the night (03:00-05:00), and rise over 100,000 during the day. The 90,000 threshold is the minimum for the 25th percentile of N_{GPS} between 08:00 and 20:00. The median value of N_{GPS} does not show a morning peak, but a 12:00-13:00 peak, then drops for the early afternoon, before increasing again over the 15:00-19:00 period. The N_{GPS} is therefore strongly time-dependent, although its dynamics do not necessarily follow those seen from the traffic loops.

In order to estimate the "amount of GPS information per link", and therefore to compare the sections of various lengths that make up the TPIM graph, the "linear density of positions for a section", $\lambda_{pos}(s,t)$, is defined from $N_{GPS}(s,t)$ as follows:

$$\lambda_{GPS}(s,t) = \frac{N_{GPS}(s,t)}{L_s} \tag{6.3.1}$$

Underlying this definition is the assumption that GPS FCD positions are uniformly scattered in space across the section. The variability of traffic conditions is then spatially reflected, at a macroscopic scale, by the state of each section. The more local information brought by the GPS FCD is uniformly flattened over the map.

Figure 6.8 gives the distribution of the linear density of positions per hour. It shows that hourly distributions are asymmetrical and dispersed. Two periods can be identified. At night, between 00:00 to 03:00, the median density and the IQR remain constant. There is a median between 0.1 and 0.2 position per m. During the day, from 07:00 to 22:00, the median is also almost constant, reaching almost 0.3 position per m, with some slight variations of the IQR. Between the two periods, a transitional period is clearly shown between 04:00 and 07:00, with a gradual increase of the median and IQR, as the 75th percentile gradually increases.

In order better grasp the dynamics behind the GPS fleet, and how they related to the general traffic fleet dynamics, the traffic dynamics of the TPIM network, as shown by the loops through the VKT_{norm} indicator (Figure 6.9) is compared with the GPS fleet dynamics through N_{GPS} (Figure 6.7) and λ_{GPS}. The comparison is done by normalizing the three variables over their respective range bounded by their respective minimum and maximum values.

It can be said from the resulting plot (Figure 6.10) that the general dynamics of the network are to be found both in the loops-based and GPS-based indicators: a night period with a 24-hour low between 03:00 and 04:00, a sharp increase of traffic in the morning between 05:00 and 07:00, and a decrease in traffic past 19:00. For the 07:00 to 19:00 period, there are nonetheless some differences.

The main difference is the "morning peak", that "breaks" the sharp increase of the 05:00-08:00 period, clearly shown by the loops (a peak at 08:00-09:00, followed by a decrease of traffic between 09:00 and 10:00) but not the GPS fleet, which after 07:00 continues to increase at a lower rate.

Both the loops and GPS show a "noon-peak" over the 12:00-13:00 period, although it is stronger for the GPS than the loops. Both then reach a low point before steadily increasing throughout the afternoon, peaking at 18:00.

The lack of a morning peak for the GPS fleet hints the actual population that may be behind the wheel. The GPS company, at the time, mostly collected data from drivers paying a subscription, i.e. relied on mostly professional clients, like taxis. This could be compatible with the observed trends: an important mid-day and afternoon peak, both of higher proportion than seen by the loops. In the case of taxis, most collect clients at the airport in the morning, and should drive into town after 09:00, which is compatible with the constant rise, slow between 08:00 and 10:00, and intensifying after 10:00, to peak at noon.

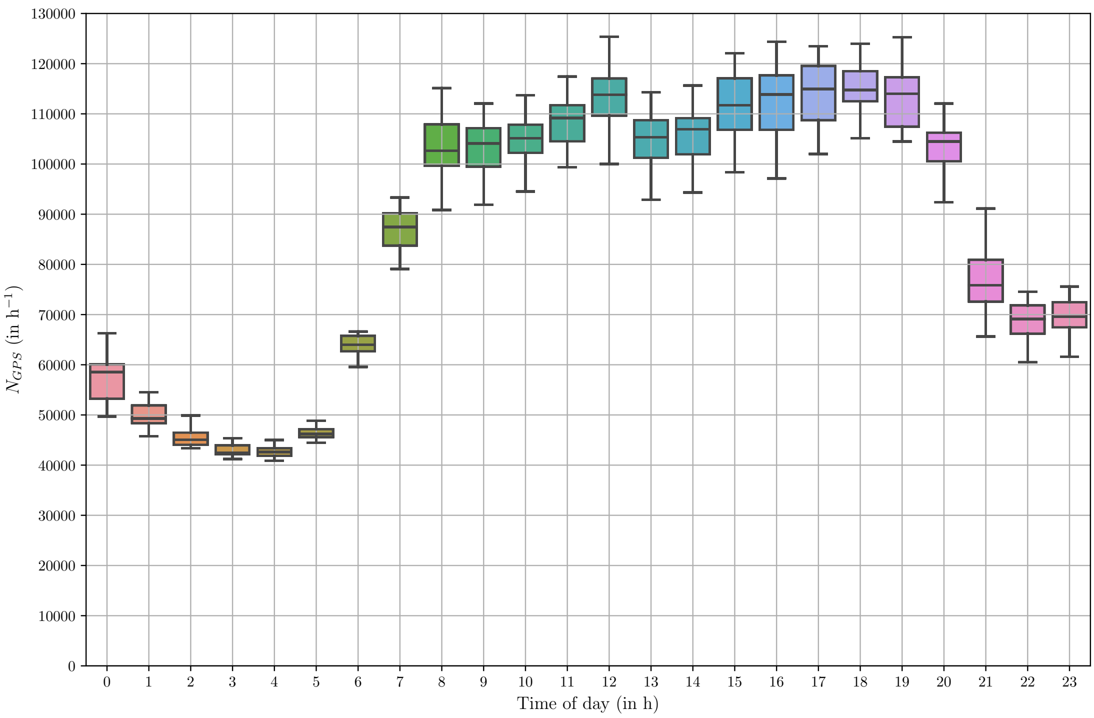

Figure 6.7 – Provider 1. First delivery. Distribution of Number of Positions N_{GPS} computed per hour and per day, over TPIM. Business days of October 2014.

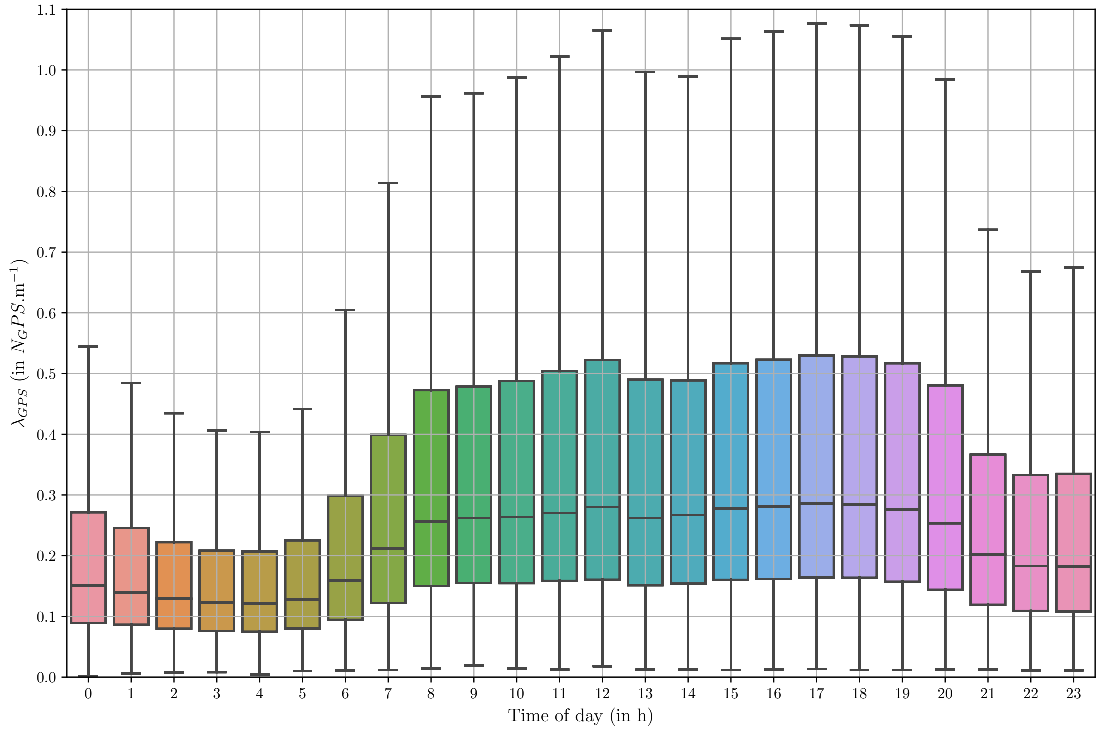

Figure 6.8 – Provider 1. First delivery. Distribution of Linear Density of Positions λ_{GPS}, computed per (section, day, hour), over TPIM. Business days of October 2014.

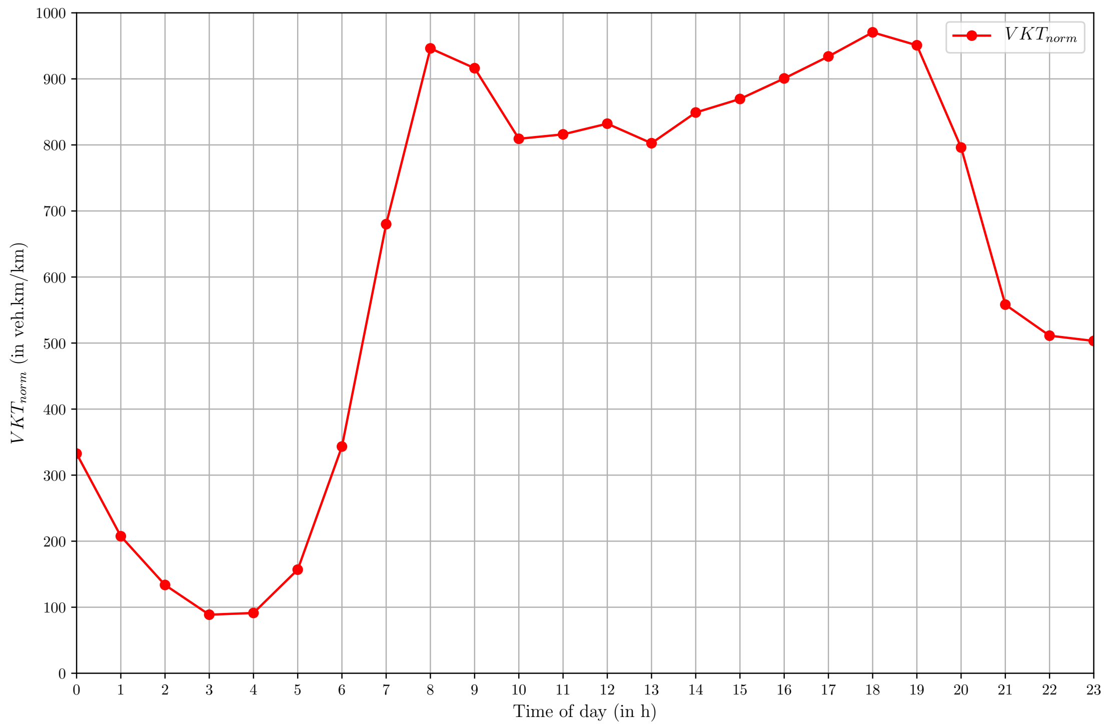

Figure 6.9 – Hourly Normalized VKT over TPIM network. Business days of October 2014.

6.3.8 Multiple records

Diving more thoroughly into the (s, t, V_{GPS}) records of the instantaneous speed table turned out an unexpected phenomenon: many (s, t, V_{GPS}) records were identical. In order to character-

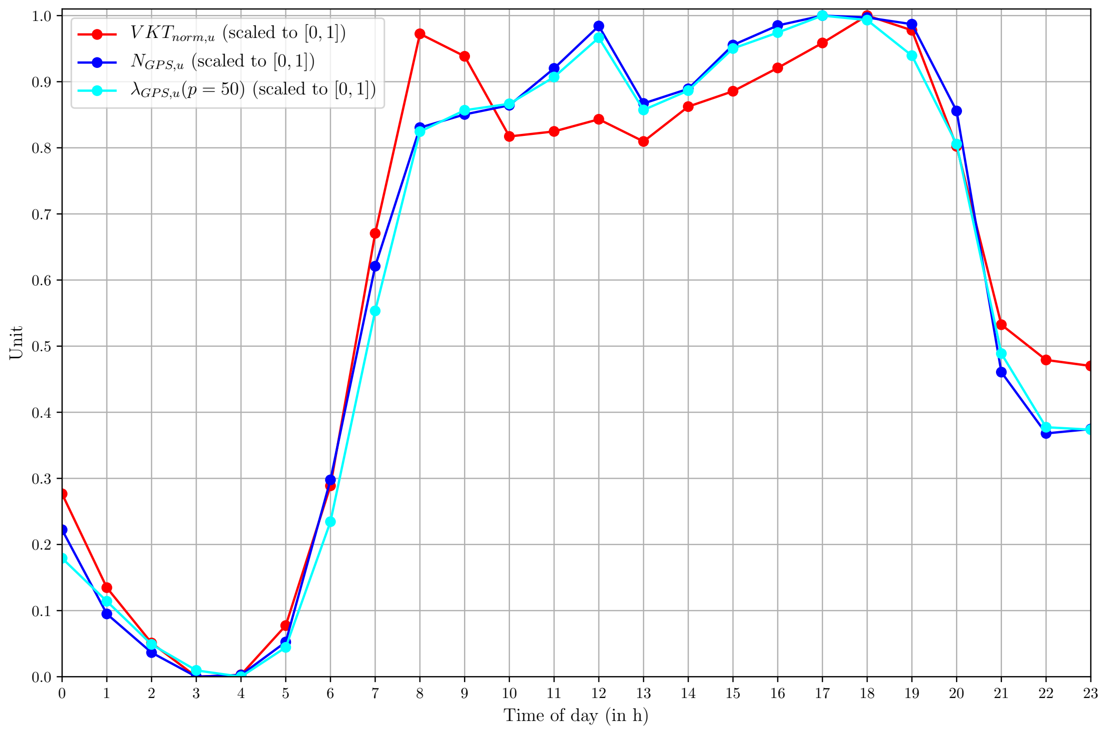

Figure 6.10 – Compared (Normalized) Hourly 1km-VKT, Number of GPS FCD Positions, Linear Density of GPS FCD Positions, over TPIM network. Business days of October 2014.

ize the phenomenon, the P1D1 was first checked for an eventual redundancy in the information contained. Then, the Author investigated whether the information redundancy was related to the speed or specific spatial positions on the network (i.e., specific sections s).

One of the way to empirically test the information redundancy is to define the "unique records table" as the table containing (s, t, v) records, with the condition:

$$i \neq j \leftrightarrow (s_i \neq s_j) + (t_i \neq t_j) + (v_i \neq v_j) \tag{6.3.2}$$

The unique records distribution is compared with the original or "multiple records distribution", as to see if there are significant differences between them both.

As previously stated, two modes are defined: the stopped mode, for speeds strictly below 5, and the running mode, for speeds above 5 and below 130 both included.

Table 6.4 shows the aggregated statistics associated with both distributions and modes. Each mode taken individually and compared with its counterpart shows identical statistics (same percentiles, same average, same standard-deviation). Figure 6.4 shows the running mode distribution, which appear extremely similar, excepted for the 55-peak which is slightly lower for the unique dataset (frequency of 0.06 % against 1.3 %).

The remarkable difference between both distributions lies within the records count, and the mix between the two modes. Within the multiple records distribution, the stopped mode accounts for 35 % of all modes, whereas within the unique records distribution, the stopped mode accounts for 22 % of all modes.

The differences in the mix-ratio of both modes has heavy consequences on the aggregated statistics, with higher speed values for the unique than for the multiple records: for instance, the median speed is 18 for the multiple records, and 24 for the unique records.

Therefore, the redundancy of information in the multiple speed values is only partial. Given

Table	Mode	Count	25th p.	50th p.	75th p.	average	st. dev.	IQR
multiple	stopped	15,570,700	0	0	0	0	1	0
multiple	running	29,797,635	19	30	42	31	15	23
unique	stopped	4,542,207	0	0	0	0	1	0
unique	running	16,328,762	19	30	42	31	15	23
multiple	all	45,368,335	0	18	36	20	19	36
unique	all	20,870,969	7	24	38	24	19	31

Table 6.4 – Descriptive statistics by table (unique or multiple records) and mode (stopped or running) of the instantaneous speed distribution of the first delivery of Provider 1, business days of October 2014.

the sampling strategy of the GPS receivers, which is time-based, a section of a given length as more chances to "see" stopped than running vehicles. This means that, for a given a period of observation δt, there is more chance for two different vehicles to send a record with $V_{GPS} = 0$ than for two different vehicles to send a record with the same strictly positive speed, like $V_{GPS} = 28$. When considering the network as a whole, this reduces the impact of the sections length, but non completely since the number of vehicles on the network does not stay constant throughout a 24-hour period. Therefore, even if the dataset contains some redundancy, especially for the running mode, there is no way to consider a double zero-speed record for a given section s and timestamp t as a redundancy.

Therefore, it was at first decided to keep the "multiple" dataset over the "unique" dataset.

After discussing with Provider 1, it turned out that some GPS receivers could send the same speed value several times in a row, and that the equipments' behavior was hardly documented, even for them. Moreover, the instantaneous speeds delivered were those "used in the computation of the average speed" through their proprietary algorithm: this triggered additional, systematic, data duplication. It was therefore agreed, for each section s and section timestamp t, to cancel out every identical speed records. The resulting dataset is known as Delivery 2, or P1D2.

6.3.9 The space dependency of the number of GPS FCD positions

As a continuation of the study of the time-dependence N_{GPS}, the spatial analysis of the number of positions N_{GPS} computed by section yielded specific places where there was a concentration of information.

A preliminary analysis was carried out for all sections of the network (beyond the TPIM), in order to identify the sections with highest absolute number of positions N_{GPS} per section s and section timestamp t. The query yielded that section $s = 38,933$ accounted for the over twenty first records returned. It was even more suprising to see that this section modeled a residential street of the XVIth arrondissement, the "rue Cortambert", not part of the TPIM network, not equipped by traffic sensors, and with no reason to have such a concentration of GPS-equipped vehicles. Moreover, all positions reported the same instantaneous speed, $V_{GPS} = 28$. After a discussion with the Provider, which itself turned towards the GPS company, it ended up being an artifact generated by GPS devices put in demonstration mode. In such a mode, a device would, whatever its actual position, send a GPS record positioned on that specific street with a speed value of 28 (and a heading of 214°, but that specific value was not included in the purchased dataset and was given in the provider's answer). The situation was therefore cleared, and all associated records deleted from the database.

Continuing the spatial analysis, Figure 6.13 shows the daily median of λ_{GPS} over the TPIM network. The GPS fleet is not uniformly spread upon the network: it is more present in the

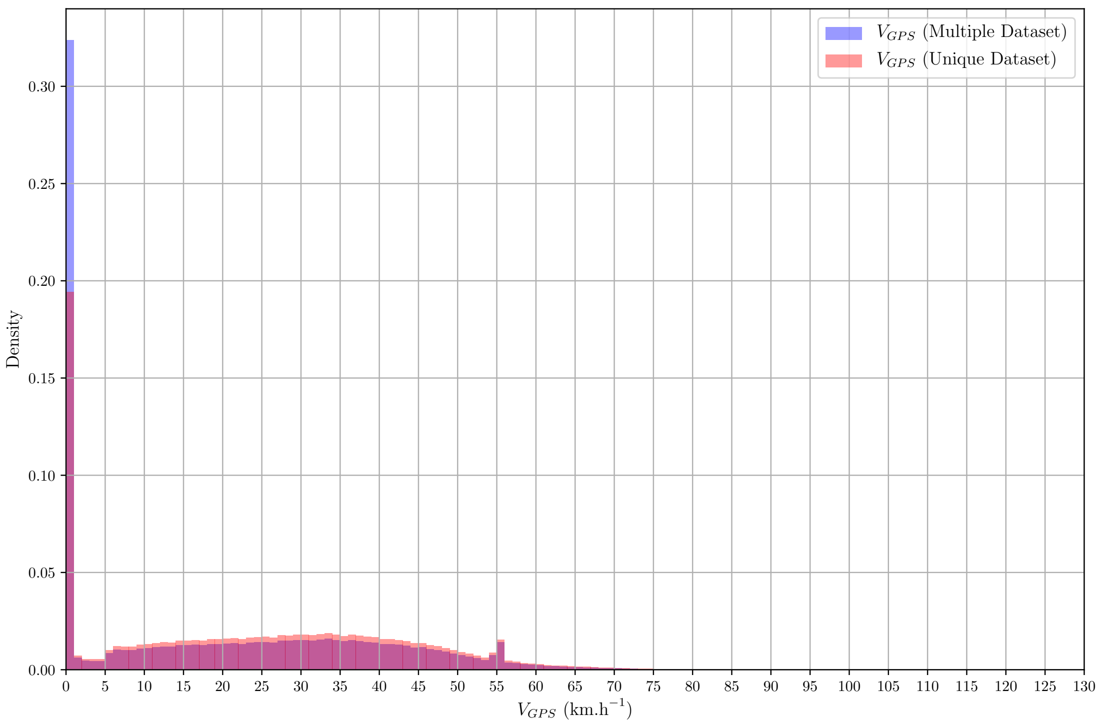

Figure 6.11 – Compared Multiple and Unique INSTV, over TPIM network. Business days of October 2014.

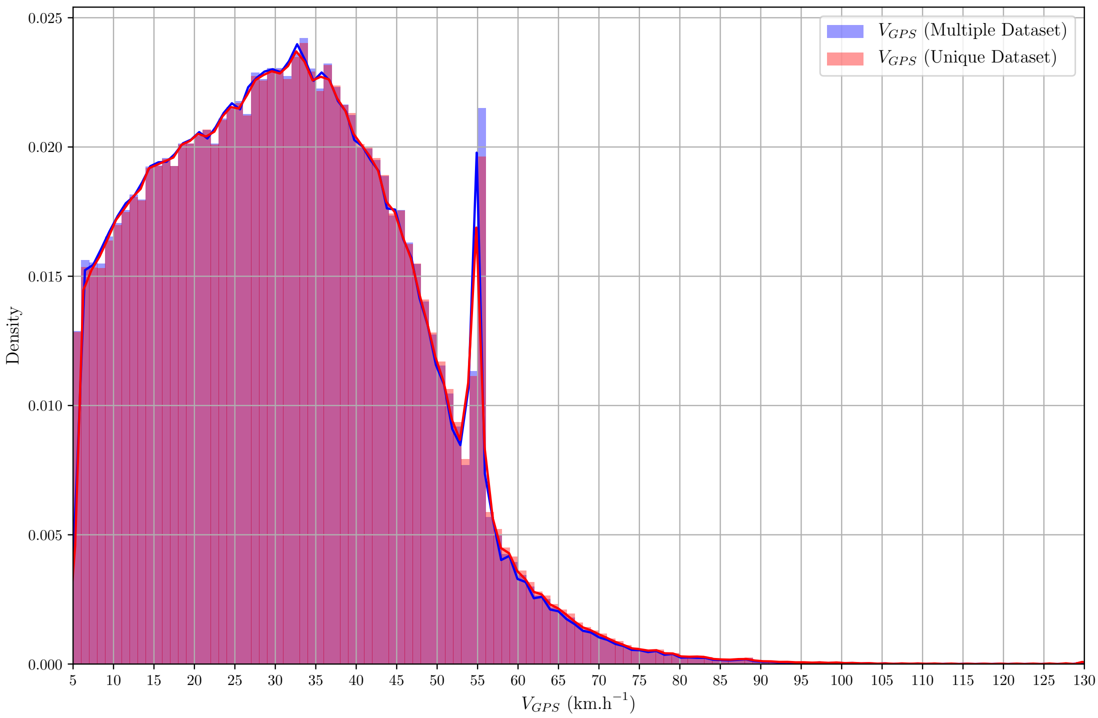

Figure 6.12 – Compared Multiple and Unique INSTV (Running mode: 5 to 130), over TPIM network. Business days of October 2014.

West, the central part of the city and around the train stations, and on the arterials that link these areas with the airports. This support the assumption, and the information given by the Provider, that the GPS fleet at the time mostly covered professional vehicles, such as taxis or company cars.

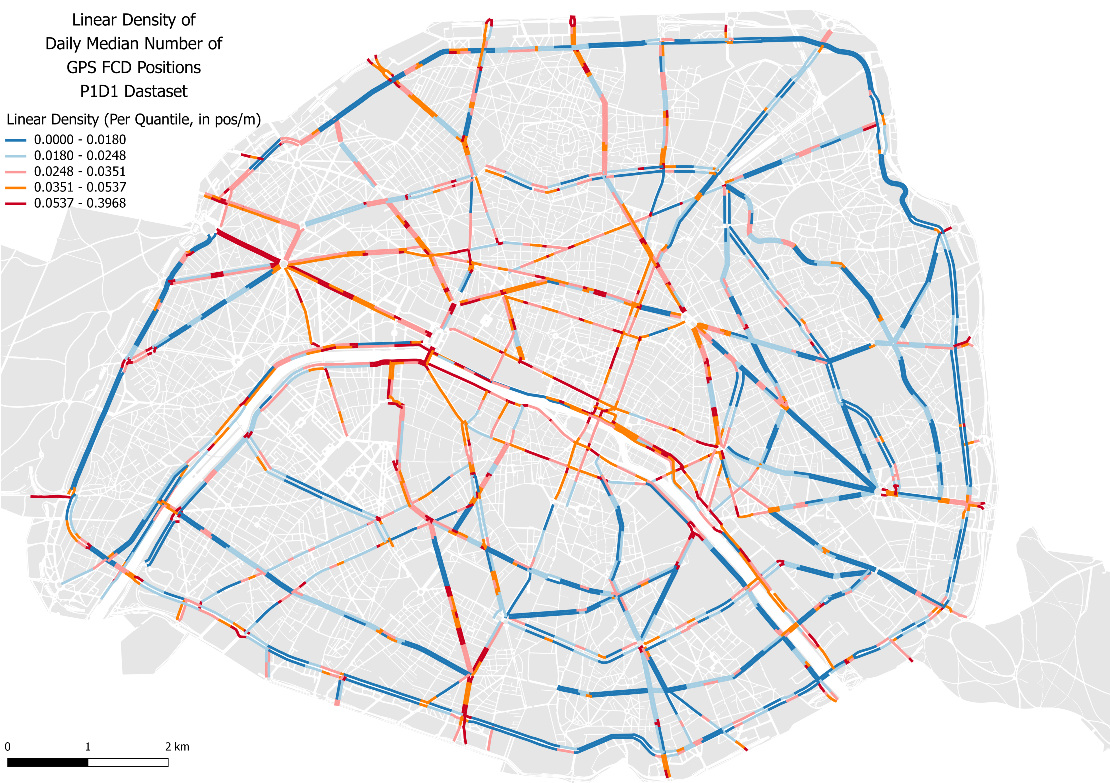

Figure 6.13 – Compared Multiple and Unique INSTV (Running mode: 5 to 130), over TPIM network. Business days of October 2014.

Beyond the traffic considerations, the first tender and its data perfectly illustrate the "back-office issues" encountered when dealing with data that are not just "smooth aggregates".

The tender allowed the Author to investigate data at an "intermediate" level of aggregation: the location of GPS point data was known per section, and the timestamp known by a timestamp depending on the section's level of traffic.

The "issues" encountered with the P1D1 dataset show the production of probe vehicle data goes through complicated technical processes and algorithms that have side-effects on the data. A honest and thorough discussion with the Provider during the one-year contract allowed to circumvent most of them. This shows that a reasonable level of openness of the private sector, while preserving their proprietary algorithms, allows constructive cooperation and improvements on both sides. The shared-interest, especially in those early days of commercial tendering for GPS data, was to improve the data reliability and show its relevance for present and future applications.

Nonetheless, the Author made a harmful mistake to correct the "multiple records" issue: by identifying redundancy in the speed values, he decided that for each section s and timestamp t, only distinct speed values were to be kept. He did not pay attention to the fact that two different receivers could effectively send the same speed value, but that the method would cancel out one of the two values.

Moreover, at the time, the only known figure for average speeds on Paris arterials was the one yielded by the BRP algorithm, circa 15 km.h^{-1}. The average speed yielded by the second delivery, referred to as P1D2, appeared to fall more in line with the values our experience was used to encounter.

The first tender was over by Summer 2015, and a new one was launched a few months later: a second provider, referred to as Provider 2, different from Provider 1, was selected in August 2016.

6.4 The second tender: confronting data from two providers

The P1D2 dataset seemed at first-hand, when compared with the BRP average speed, totally satisfactory. This section presents the second tender, won by Provider 2 for a two-year period (2016-2018). Provider 2 is not Provider 1, but gets his GPS raw data from the same GPS company and hence the same fleet.

The first delivery of Provider 2, known as "Provider 2 Delivery 1" (P2D1), offered an opportunity to continue the investigations on the FCD datasets. It also gave the PCE Lutèce a new reference regarding average speeds in Paris, and therefore to compare both the P2D1 data with the P1D1 and P1D2 GPS FCD, and the BRP, datasets.

This section presents the confrontation between the Provider 1 and Provider 2 datasets.

6.4.1 Changes from the first tender

In 2016, a new tender was launched, to follow up on the first one that had expired in Summer 2015. The tendering process selected a new provider, which will be called Provider 2. Provider 2 gets its data from the same GPS receiver fleet as Provider 1.

The purpose remained the same as the first tender: buy, for a section s and a timestamp t, with a given refresh rate, GPS speed data: an average speed, and instantaneous speed values.

Based on the experience of the first tender, the tender specifications were modified.

6.4.1.1 A new definition for sections' refresh rates

The first modification was made on the road network graph. The purpose was to synchronize all the sections timestamps and refresh rates with the one used by the SURF traffic management system, or at least with a multiple of it. Traffic sensors data is elaborated on a three-minute basis (HH:00, HH:03, HH:06, etc.).

Four categories of roads were defined, as described in Table 6.5, based on both their traffic level (so that a 3-min refresh rate makes sense) and their inclusion in the main arterial TPIM network on which VKT_{norm} and V_{BRP} indicators are drawn from the traffic sensors implemented on them. The categories division also reflects a funding issue: the higher the refresh rate, the higher the price of data per kilometer. The choices made prioritize the statistical (hence category 1) network (made up of the TPIM main arterials and the ringway) over other roads not included in it. Therefore, on the TPIM main arterial road network, on which the BRP speed indicator is computed, all sections were aligned on the three-minute refresh rate. This was also transposed on the ringway for the sake of homogeneity, even though its specific traffic sensors elaborate data every minute. More local roads, with lighter traffic and/or, not included in the statistical network, were dispatched in categories 2 and 3. Category 4 was a special one for the Bois de Boulogne and Vincennes, outside of the ringway but part of the city's road network, and not equipped with traffic sensors.

Category	Total length (km)	Estimated traffic levels (ADT by way)	Data refresh rate (min)
1	530	Above 15,000 *or* part of the statistical network	3
2	280	Between 5,000 and 15,000 *or* above and not part of the statistical network	6
3	560	Below 5,000 *and* not part of the statistical network	15
4	115	Bois de Boulogne and Vincennes (variable traffic levels)	6

Table 6.5 – Sections of the second tender road network oriented graph: categories and associated cumulated lengths and average traffic levels.

6.4.1.2 A new definition for instantaneous speed data

The second modification modified what was understood as instantaneous speed data. For a given section s and section timestamp t, the phrasing switched from "instantaneous speed values associated with the average speed" found in the first tender to "the full list of instantaneous speeds collected on the section s, during the time interval ending at t". By full list were understood speeds retrieved from all GPS raw records (or GPS FCD point positions) map-matched to the section, even in the case of multiple signal emission by the same receiver.

This was clearly stated so as to avoid the complications met with the Provider 1 dataset.

6.4.2 Data comparison between Provider 1 and Provider 2

After some work on the road network map, the first data delivery, P2D1, of Provider 2 was made in November 2016.

The first analysis work on the P2D1 dataset was to compare with the P1 datasets: at first, with the P1D2, which was until then considered the "reference" for Paris FCD data[4]. This was done by comparing the instantaneous speed distribution from P1D2 with the one from P2D1.

At first, the Author did not intend to order 2014 data, already supplied by Provider 1, from Provider 2. With October 2015 and October 2016 data from Provider 2 at hand, instantaneous speed distributions were compared with P1D2. Network-wise, common grounds were used: the well-known TPIM main arterials network.

6.4.2.1 Compared distributions of instantaneous GPS speeds

Aggregated statistics (Table 6.6) showed very important discrepancies between the two datasets. First, the number of records involved in P2D1 compared with P1D1: P2D1 includes almost four times more records than P1D2. Even if there was an increase in GPS-enabled vehicles from 2014 to 2015, this alone could hardly explain such an increase. When looking by mode at the data, the running and stopped mode are approximately balanced in the P1D2 dataset, while they tend to a 33 % to 66 % ratio for the P2D1 dataset. The median speed for P1D2 is 8 km.h^{-1}, the average speed 15 km.h^{-1} (in line with usual BRP values), whereas for P2D1 the median speed is 23 km.h^{-1} and the average speed 24 km.h^{-1}. No reasonable physical explanation could be found for such differences, except that the record numbers differences hinted some issue in the way the data was filtered by either Provider 1 or Provider 2. Provider 2 confirmed that the

[4]The second delivery P1D2 of Provider 1 sees instantaneous speed duplicates systematically removed.

Table	Mode	Count	25th p.	50th p.	75th p.	average	st. dev.	IQR
P1D2	running	3,954,057	16	27	39	28	15	23
P1D2	stopped	3,359,901	0	0	0	0	1	0
P1D2	all	7,313,958	0	8	29	15	18	29
P2D1	running	19,244,392	20	32	43	32	16	23
P2D1	stopped	7,210,849	0	0	0	0	1	0
P2D1	all	26,455,241	1	23	39	24	20	38

Table 6.6 – Descriptive statistics by dataset (Provider 1 Second Delivery and Provider 2 First Delivery) and mode (stopped or running) of the instantaneous speeds. Business days of October 2014 (P1D2) and October 2015 (P2D1).

data treatment was sticking to what had been specified in the tender, and that the dataset was map-matched GPS raw record instantaneous speed, with no filter.

Were the algorithms from Provider 2 generating artificially multiple speed records, like seen in the first delivery of Provider 1? What part of the increase in records' number can be attributed to the increasing vehicle fleet?

In order to clear out discrepancies induced by evolving traffic conditions and increasing GPS FCD vehicle fleet, October 2014 data was ordered from Provider 2. The goal was then to compare, on the same time-frame (business days of October 2014) and over the same network (TPIM), instantaneous speed datasets of both first P1D1 and second P1D2 deliveries of Provider 1, with first delivery P2D1 of Provider 2.

Table 6.7 gives the usual descriptive statistics. First, looking at the records count, the P1D1 delivery holds more records than the two other P1D2 and P2D1 deliveries combined. A thorough discussion with Provider 2 secured the P2D1 dataset, which respected point by point the tender's requirements, i.e. speeds retrieved from all GPS raw records (or GPS FCD position) map-matched to each section. That means that the records count of P2 data includes the duplication behavior of some GPS receivers, but not some side-effect of a computational algorithm like in the P1D1 dataset. Nonetheless, the duplication effect of the P1 algorithm only partially affected the instantaneous speed records, as the aggregate statistics show: the running mode median speed is 30 for P1D1 (IQR is 22) and 33 for P2D1 (IQR is 25), and the running mode average is 31 for P1D1 (standard deviation is 15) and 33 for P2D1 (standard deviation is 25). If the running mode was not too affected, the mix between stopped and running mode, and the resulting aggregate all-mode statistics, showed stronger divergences: the running–stopped ratio for P2D1 is 74 %–26 %, while it is 65 %–35 % for P1D1, and 54 %–46 % for P1D2.

Figure 6.16 shows the compared empirical distribution of instantaneous speed values for the running mode of the three datasets. The 5–30 speed range shows the striking differences between the P1D2 dataset on one hand, and the P1D1 and P2D1 datasets on the other, even though all three are based on the same GPS receivers fleet. P1D2 shows a greater, nearly constant density of values over this range, whereas both P1D1 and P2D1 show a gradual increase. For speeds above 30, the P1D2 dataset decreases more sharply than P1D1 or P2D1. If P1D1 and P2D1 follow the same trend, P1D1 remains above P2D1 for speeds below 40; above 40, P1D1 decreases more sharply than P2D1. Finally, the 55 peak is higher for P2D1 than for P1D1 and P1D2.

To sum up the observations betwen the three datasets:

- P1D2 is a dataset biased by the deletion of receivers duplicates;
- P1D1 and P2D1 follow the same trends, but P1D1 is influenced at least for a part by Provider 1 average speed algorithm that produced it. The slight variations caused by the

Table	Mode	Count	25th p.	50th p.	75th p.	average	st. dev.	IQR
P1D1	running	9,546,927	19	30	41	31	15	22
P1D1	stopped	5,065,435	0	0	0	0	1	0
P1D1	all	14,612,362	0	18	35	20	19	35
P1D2	running	1,246,009	16	27	39	28	15	23
P1D2	stopped	1,071,661	0	0	0	0	1	0
P1D2	all	2,317,670	0	8	29	15	18	29
P2D1	running	4,464,561	20	33	45	33	16	25
P2D1	stopped	1,544,820	0	0	0	0	1	0
P2D1	all	6,009,381	2	24	40	25	20	38

Table 6.7 – Descriptive statistics by dataset (Provider 1 P1D1 and P1D2 deliveries, Provider 2 P2D1 delivery) and mode (stopped or running) of the instantaneous speeds. Business days of October 2014.

algorithm render it hardly usable when compared with data not part of it.

- P1D2 is the closest to the GPS raw data records: the only possible bias introduced between the data generated by the receivers and the data delivered is the map-matching process. P1D2 therefore includes duplications generated by the receivers.

On operational grounds, this yields concerns when using GPS FCD datasets to assess the consequences of a speed-limit measure, like the lowering of the speed of a specific arterial or zone. For instance, between P1D1 and P1D2 (same provider), the median speed is 18 for the first dataset, and 8 for the second; between P1D1 and P2D1, which apparently are the closest, the median speed is 18 for P1D1, and 24 for the second. This also underlines the importance for the TMC to specify, in details within the tender, what is expected.

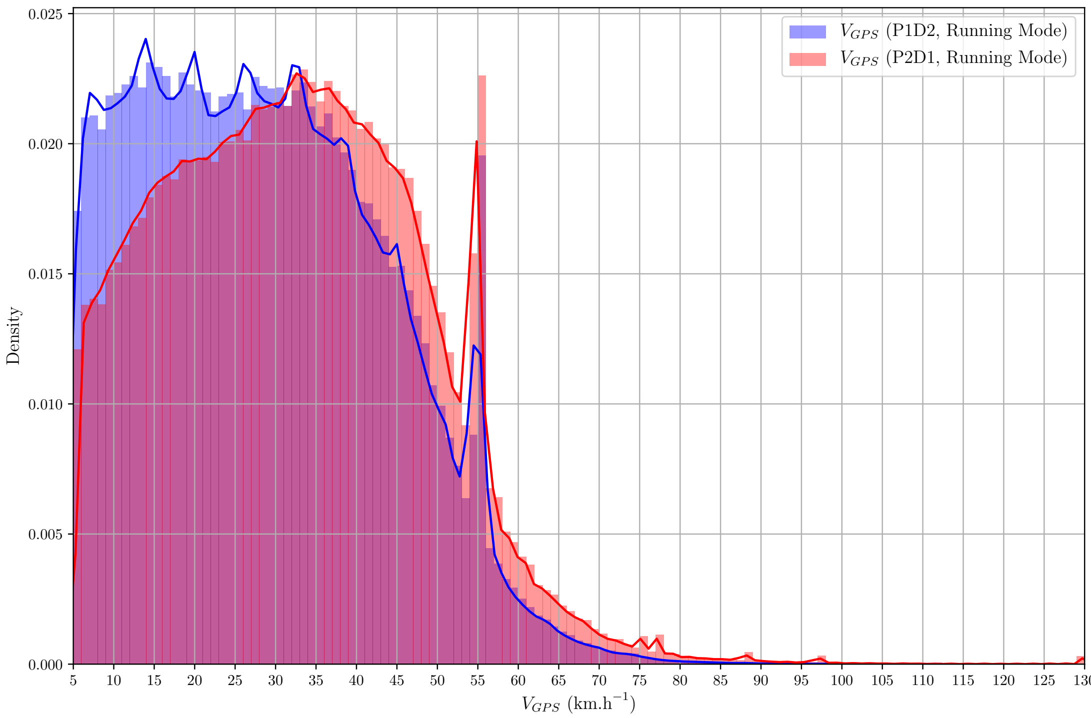

Figure 6.14 – Compared P1D2 and P2D1 Over TPIM (Running mode [5,130]). Business days of October 2014 (P1D2) and October 2015 (P2D1).

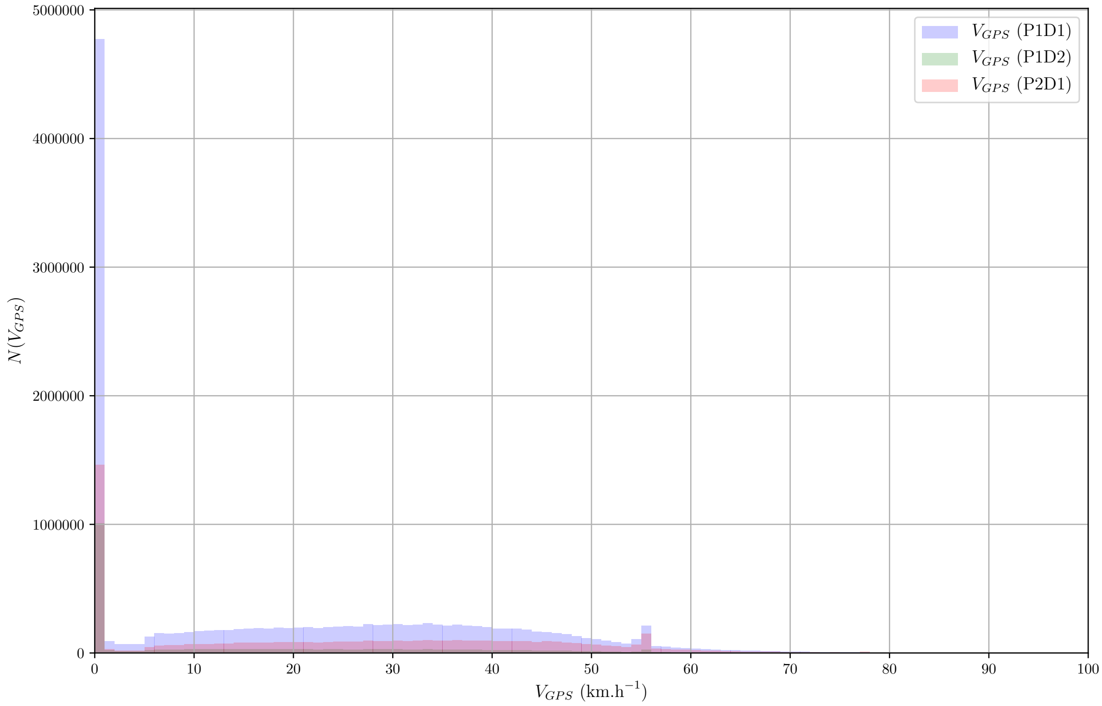

Figure 6.15 – Compared P1D1, P1D2 and P2D1 Over TPIM. Business days of October 2014.

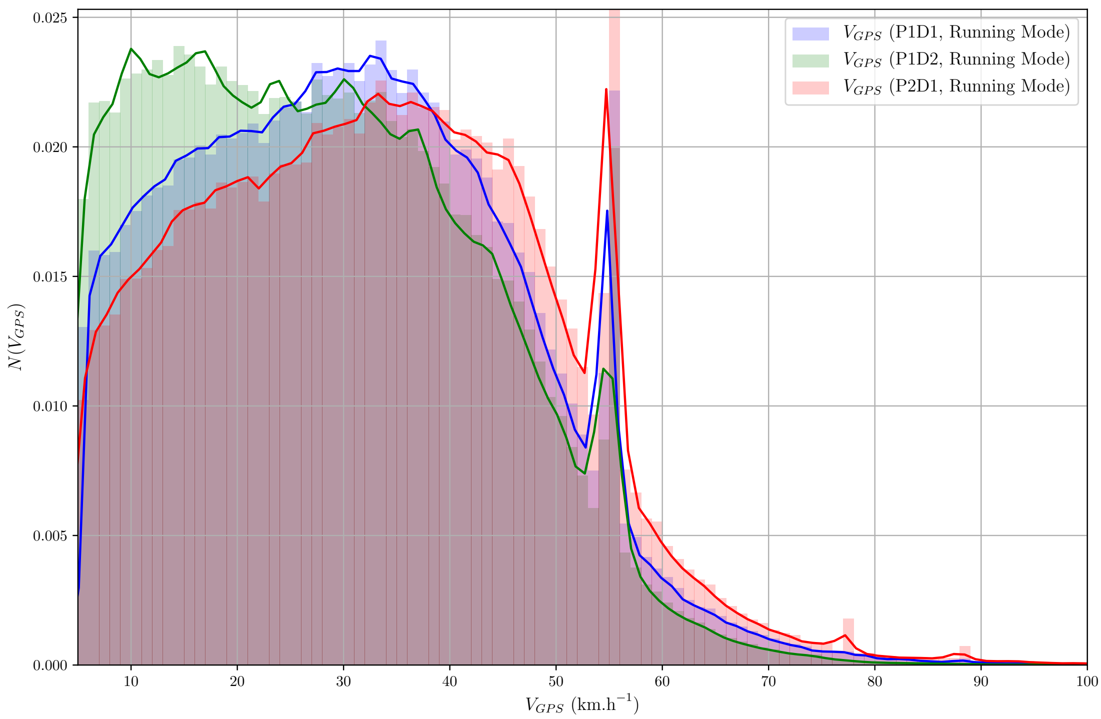

Figure 6.16 – Compared P1D1, P1D2 and P2D1 Over TPIM (Running mode). Business days of October 2014.

6.4.2.2 Time series and the importance of sections' refresh rate

Complementary to the distribution, an analysis was carried over the time-series of the median speed per t_{03min} time-slots taken over all business days of October 2014. Recall that 3 minute is the elementary time aggregation interval of the traffic loops data. Sections of the P1 map were

Map	Section category	Refresh rate (min)	Length (km)	Total length ratio (%)
P1	1	3	6	2
P1	2	6	40	11
P1	3	10	233	63
P1	4	10	89	24
All	–	368	100	

Table 6.8 – Length of each section category within the TPIM network.

refreshed according to their estimated traffic levels, i.e. sections part of the TPIM network have various refresh rates (3, 6 or 10 min), whereas all sections in the TPIM of the P2 network have a refresh rate of 3 min. When flooring all observations into 3 min intervals, this means that with the mentioned heterogeneous refresh rates, the sample size per interval will be varying.

Figure 6.17 shows the sample size (number of records) $N_{GPS}(t)$ per t_{03min} slots, for the three P1D1, P1D2 and P2D1 dataset. P2D1, because of its homogeneous section refresh rates, offers a continuous curve. P1D1 and P1D2 are worth closer investigation.

Figure 6.18 shows $N_{GPS}(t)$ per t_{03min} and per section category for the P1D1 dataset: the curves show what Figure 6.17 hinted: the four categories represent four distinct curves of N_{GPS}.

Figure 6.17 represents the sum, per t_{03min}, of these four curves. Whether a category is present in a given t_{03min} depends on the result of the section timestamp t (which is shared by all sections in the same category, hence $t = t_{cat}$) floor-division by the t_{03min} timestamp value.

The number of records per category also relates to the corresponding lengths. Table 6.8 shows the section length per category within the TPIM network, for the P1 map. Number of positions for category 1 is well below in terms of number of records, but also accounts only for 2 % of the TPIM length. Category 2 and 3 do not account the same length proportion at all (11 % for category 2, 63 % for category 3, which makes the latter the most important) and do not have the same refresh rate (6 min for category 2, 10 min for category 3). Nonetheless, they seem to show the same general dynamics throughout the 24 hours: at night time (lowest point around 04:00), morning (08:00-09:00) and evening (plateau between 15:00 and 20:00) peaks. Category 4, which like category 3 has a refresh rate at 10 min, has a number of positions in roughly the same range as category 2, even though it is second, behind Category 3 and ahead of category 2, kilometer-wise (24 % for category 4 vs 11 % for category 2).

These observations yield the following statements, on the number of positions N_{GPS} during time-intervals of length Δt (here, $\Delta t = 3\ min$), over a network of length L (here, $L = 368\ km$) made up of sections with various refresh rates and lengths:

- N_{GPS} depends for a part on the refresh rates δt_s of the various sections s, and how these relate to Δt (ratio $\frac{\delta t_s}{\Delta t}$), but is not necessarily a monotonous (increasing or decreasing) function of it;
- N_{GPS} depends for a part on the lengths L_s of the various sections, and how these relate to L (ratio $\frac{L_s}{L}$), but is not necessarily a monotonous (increasing or decreasing) function of it;
- N_{GPS} depends on the speed of the vehicles.

The N_{GPS} per link category's consequences can be seen in the median instantaneous speed time series per delivery: as Figure 6.19 shows, there is clear split of the speed curve for Provider 1 P1D1 and P1D2 data into two to three subsets, the varying sample size per t_{03min} time-slot being behind the phenomenon. P2D1 median speed, which relies on a homogeneous section's refresh rate, is made up of one continuous set of values that vary throughout the day.

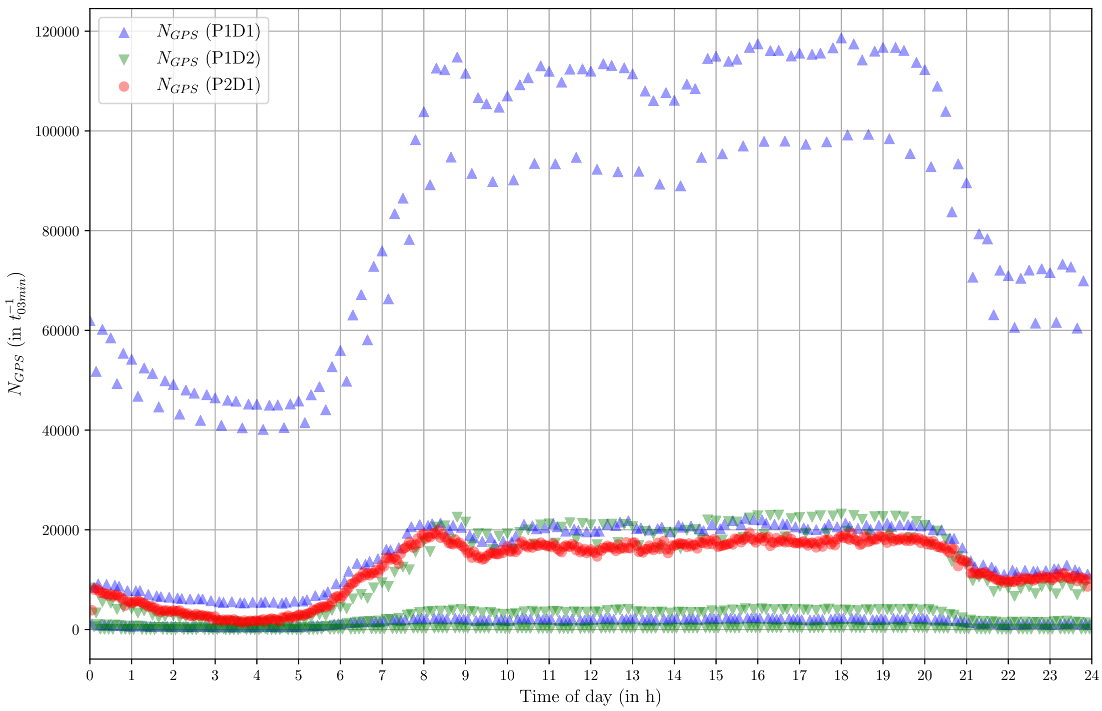

Figure 6.17 – Compared Number of Records per 3mn time-slot, for P1D1, P1D2 and P2D1 datasets. Business days of October 2014.

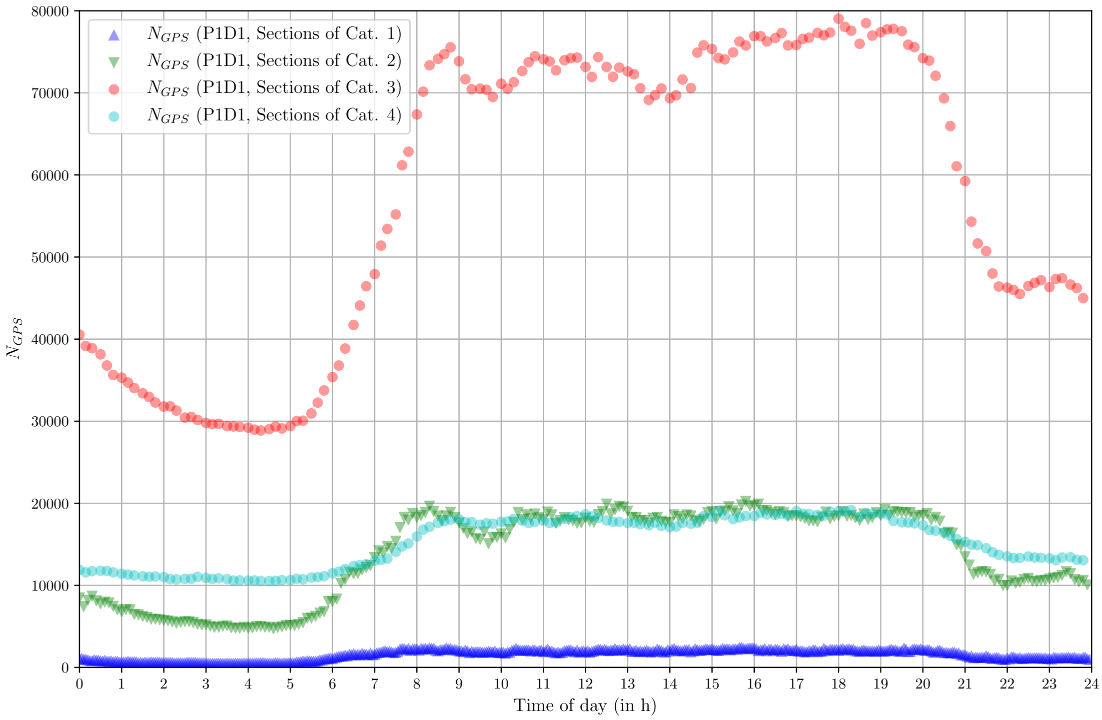

Figure 6.18 – Compared Number of Records per 3mn time-slot, per section category, for P1D1 dataset. Business days of October 2014.

6.4.2.3 Differences in average speeds

So far, the analysis have focuses on instantaneous speed distributions, which are the closest to the data generated by the GPS receivers. Nevertheless, the average speed remains the main

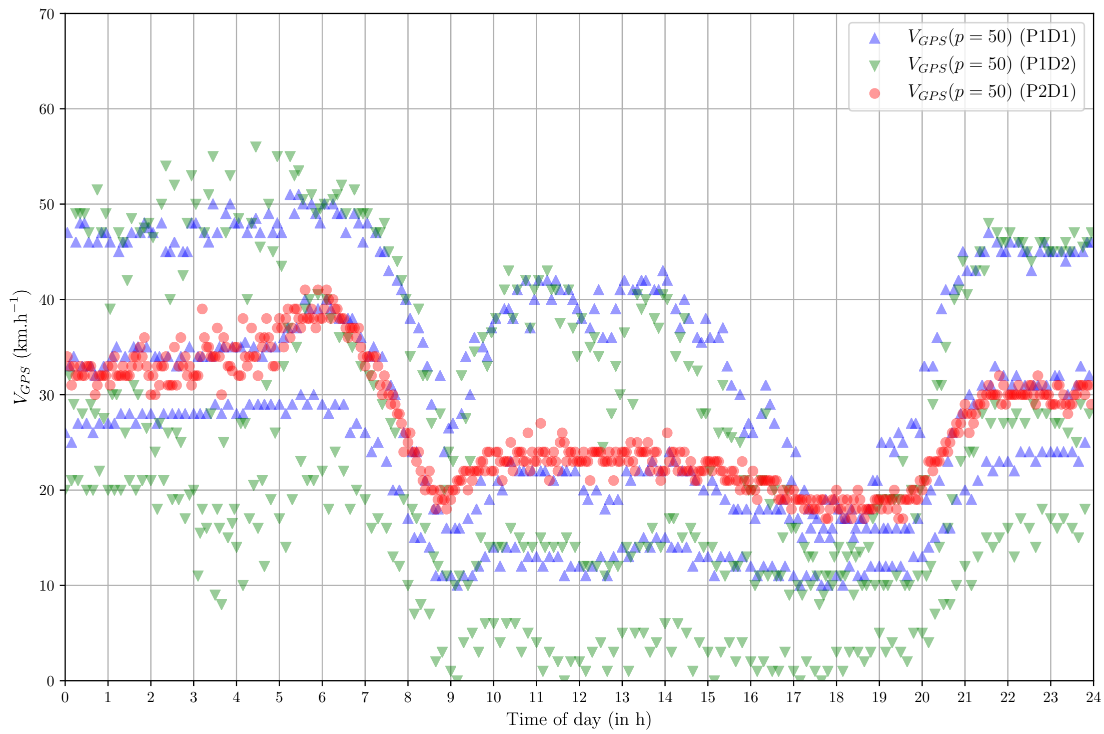

Figure 6.19 – Compared P1D1, P1D2 and P2D1 Over TPIM (Running mode). Business days of October 2014.

figure used by traffic managers: for each road segment s, and timestamp t, an average speed $\overline{V_{GPS}}$ is computed, using some algorithm, and based on instantaneous speed data. The instantaneous speed data used generally is the one effectively collected during the time interval timestamped t, but some providers complement it with historical data in case they lack real-time data. P1 used a proprietary algorithm, P2 computed the arithmetic average of instantaneous speeds effectively collected (no average speed was therefore computed for time periods with no data available. Note this is in line with standard SQL behavior: an `AVG(NULL)` query returns `NULL`.

Each average speed is computed per section s and timestamp t.

The following averages are compared:

P1AVG the average speed produced by the proprietary algorithm of P1 (only on sections falling in category 1, 2, or 3);

P1ARITHM the arithmetic mean of instantaneous speeds of the P1D1 dataset (which is the dataset of instantaneous speed used in the P1 algorithm computations);

P2AVG the average speed produced by P2, which is the arithmetic mean of instantaneous speeds of the P2D1 dataset;

P2ARITHM the arithmetic mean of instantaneous speeds of the P2D1 dataset (which should be equal to the average speed produced by P2).

Figure 6.20 shows the distribution of the four datasets, and table 6.9 the associated descriptive statistics. For the sake of clarity, P2ARITHM is not represented, as it is exactly equal to P2AVG.

In the three cases, the overall median speed is very close: 23 for P1AVG, 20 for P1ARITHM, and 21 for P2AVG.

The average speed P1AVG is a very smooth, unimodal distribution, with a reduced dispersion when compared with the other datasets (lowest IQR). When compared to P1ARITHM (which is computed on the exact same instantaneous speed dataset, P1D1), note that P1AVG bears nearly

Dataset	Averages	Count	25th p.	50th p.	75th p.	average	st. dev.	IQR
P1D1	P1AVG	5,720,352	16	23	32	26	14	16
P1D1	P1ARITHM	7,198,158	10	20	32	22	16	22
P2D1	P2AVG	4,382,696	4	21	36	22	18	32
P2D1	P2ARITHM	4,382,696	4	21	36	22	18	32

Table 6.9 – Descriptive statistics by average speed type. Business days of October 2014.

no zero speed values, whereas P1ARITHM shows a different reality, with an empirical density of nearly 0.10 for zero speed values. P1ARITHM is more spread than P1AVG, and is bimodal, including more lower speed values (below circa 15) than does P1AVG.

Like P1ARITHM, P2AVG is also bimodal. It presents the highest density (over 0.20) of zero speed values, and then a much flattened distribution, which translates into the highest observed dispersion (IQR of 32).

It can reasonably be assumed that P1AVG does not show a zero-average speed for any section s and timestamp t because the algorithm somehow makes use of archived data, and compensates the presence of only zero-speed values for a given s and t by historical data.

Note that the deterministic peak that appeared in previous instantaneous speed distributions is clearly visible on P1ARITHM and P2AVG, at speed values 54 and 55. This is a direct translation of the observed peaks in the instantaneous speed distributions.

This shows how various algorithms (proprietary P1 or arithmetic speed) can yield an almost identical median (23 againt 20 against 21), "quite close" averages (26 against 22 against 22, although a 4 km.h^{-1} speed difference over a month-period can be considered meaningful), but this apparent closeness of aggregate values in fact covers very different situations.

This point is illustrated when looking at the time series of median of the averages distributed per t_{03min}, as shown in Figure 6.21. The curves for P1AVG and P1ARITHM are split into three "sub-curves" because of the different sections refresh rates. This is similar to the behavior observed for N_{GPS}.

The compared analysis of the GPS FCD data coming from two different providers, but based on the same GPS receivers, shows how important it is for a Traffic Management Center to clearly define what is wanted when tendering for traffic data, whose production is de facto outsourced.

Among the technical points, the first key point that it is mandatory to have a homogeneous time-frame Δt of observation over the network being studied. As Buckley [20] puts it in his review of "Road traffic counting distributions," "the introduction of Δt means that the counting distribution is somewhat more artificial than the headway distribution because it includes information about how the process is observed as well as about the process itself" ([20, p. 106]). Hence having a homogeneous process of observation over the network means the artificiality introduced by the process is somehow stationary across successive instants and locations.

The second point raised is about the widely used aggregate figures, such as median and mean, etc. Between two datasets, these can at first sight be somewhat close, but cover very different realities as to the "raw data" they are computed out of. Even in the case of the same receivers fleet, different providers means different intermediaries between the receivers' data and the tender's datasets. Hence it means different algorithms, that produce intermediary datasets that can have little to no common points, except in resulting in somewhat identical averages. Characterizing distributions in more details, with relevant descriptive statistical indicators (IQR, standard deviation, percentiles, ...), unveils what is behind apparently homogeneous datasets, and the physical or algorithmic processes at stake.

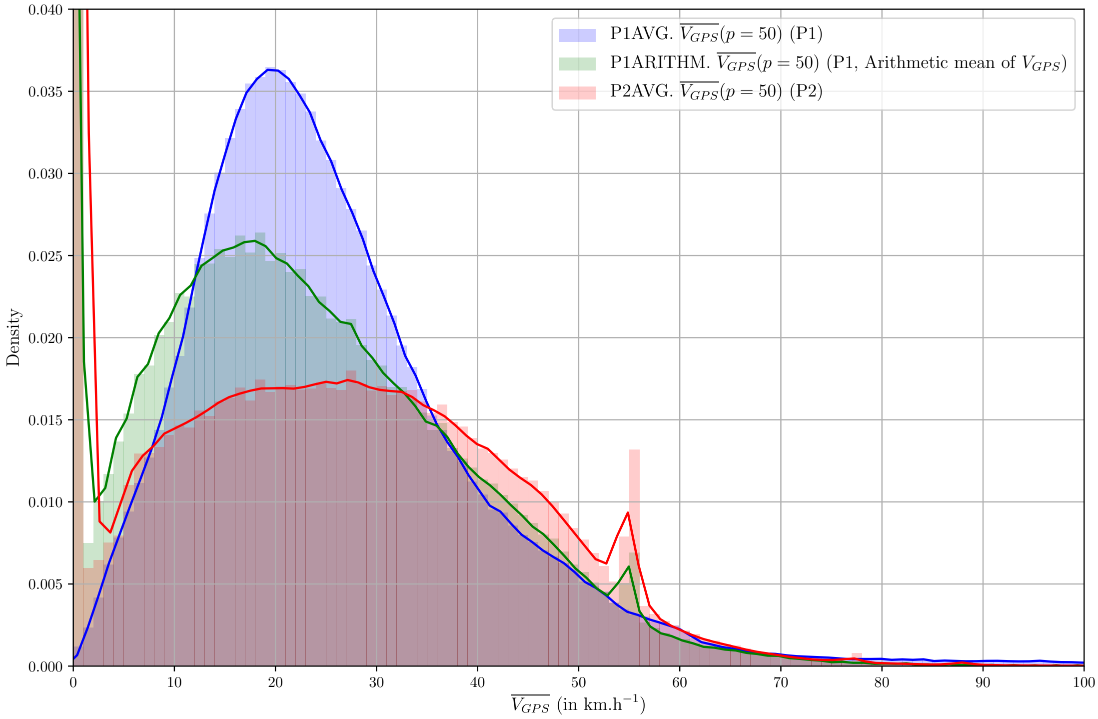

Figure 6.20 – Distributions of the Medians of the Average Speeds per section s and timestamp t, from P1 and P2. Business days of October 2014.

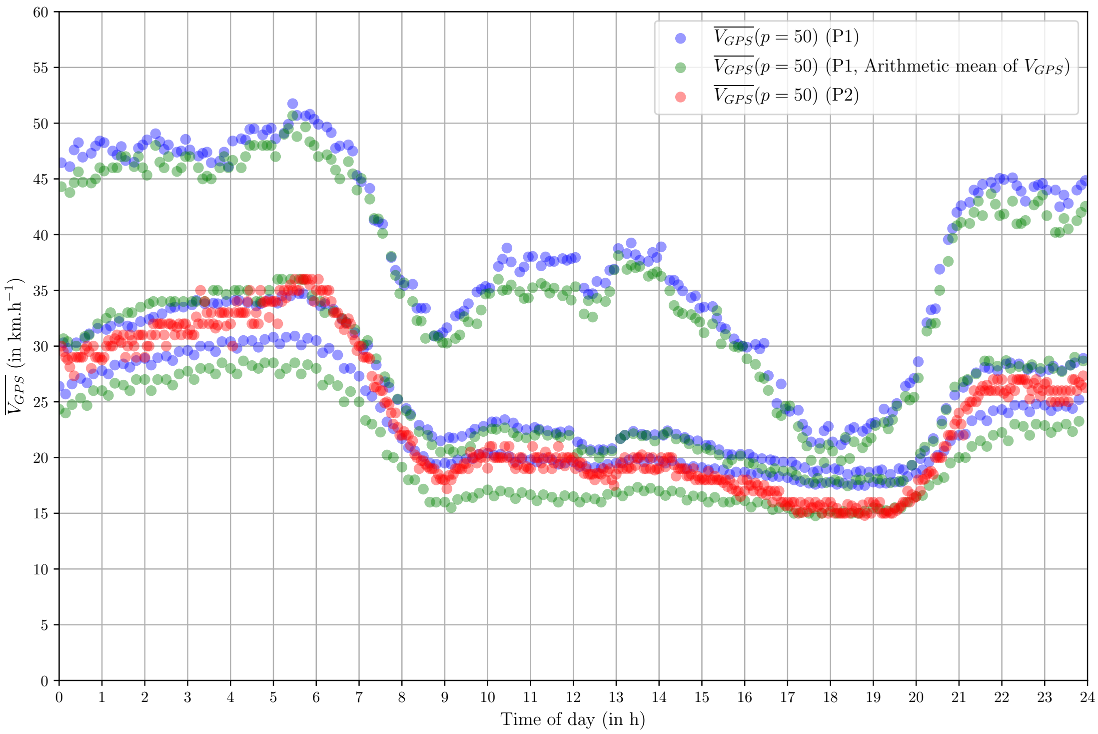

Figure 6.21 – Time-series of the Medians of the Average Speeds per section s and timestamp t, from P1 and P2. Business days of October 2014.

6.5 Conclusion: Lessons learned, a guideline of good usage

With all the observations previously made on the various GPS FCD instantaneous speed datasets, this concluding section aims at drawing some general guidelines for a Traffic Management Center, on how to deal with (offline) GPS FCD speed datasets.

6.5.1 The road network graph, and the question of the sections definition

Traffic Management Centers have often inherited some sort of representation of their road network. In France this is often called the synoptic. GPS FCD data, be it for offline statistics (as in the case of the City of Paris tender) or for real-time feeding, requires a map, acting as an intermediate layer between the unprojected (not map-matched) GPS raw records and the network's schematic representation.

In the tender, the PCE Lutèce proposed a network model, already described above, that was an oriented graph, so as to have an easy way of separating directions on bidirectional roadways. The Providers directly map-matched their GPS data on it. Networks that represent even bidirectional roadways as one geographical object, with additional attributes to specify directions, should be avoided as they may impede easy processing on the TMC's side; for instance, computing statistics on a specific direction of a bidirectional road with no distinct sections for each of the direction. Moreover, a strict symmetry in terms of sections definitions between two directions implied by the one-section-for-two-directions strategy does not always make sense, like if there is a traffic light in one direction but not in the other.

Defining the sections is a major point. Often, part of the divisions are inherited from the previous representations. In an urban setting, intersections very often define begin and end points of the sections. For Paris model, a section often goes from one signalized junction to another.

The GPS data itself is defined, and aggregated, both through time and space: a section s and its timestamp t defined a rectangular area $\delta t \times \delta x$ within the $t--x$ plane. A rule-of-thumb can be given as to a "minimum" length and time-frame.

Suppose the base rule for GPS raw record emission, that is outside any event-triggered emission, is a fixed-time interval for each receiver, like each δt. Each section on the network is observed homogeneously with a common time base and a δt refresh-rate. A vehicle with an average speed of $\overline{V}$ will travel a distance $d(\overline{V}) = {}^{\overline{V}}\!/_{\delta t}$ between two emissions.

Another factor is to have an idea of the minimum penetration rate within the traffic flow on the section, especially when traffic is heavier: say it is $\alpha(\delta t) = {}^{n_{GPS}}\!/_{n}$, with n_{GPS} the number of vehicles equipped with GPS receivers and and n the total section's flow.

An appropriate section's length δx would be, knowing the average speed on the section $\overline{V(\delta t)}$, to look at the ratio of the distance traveled one GPS receiver between two emissions $d(\overline{V(\delta t)})$ by $n_{GPS} \times \delta x$. If this is less than 1, the length is appropriate:

$$\frac{d(\overline{V(\delta t)})}{n_{GPS} \times \delta x} = \left(\frac{\overline{V(\delta t)}}{\delta t}\right) \times \left(\frac{1}{n_{GPS} \times \delta x}\right) \tag{6.5.1}$$

This rule-of-thumb may of course be adapted in settings with very close traffic lights, which will have priority on defining the sections on top of any other considerations.

Finally, map-matching strategies may differ from one provider to another. In an urban setting, which introduces some uncertainty of the exact vehicle's location if only based it on coordinates and heading, individual trajectory computation can help infer the actual roads it most probably used.

6.5.2 Offline data for statistics

The most basic offline or real-time GPS speed data that is bought is the average speed per section δx and period δt.

The average speed is subject too much discussion as to how it relates to predating sensors measurements. More thought will be given on this later in the next Chapter, but the major point is that whereas a sensor only measures at a specific location $x_0 \in \Delta x$, the GPS FCD average speed results in the sampling of traffic conditions (speed) both in $x \in \delta x$ and $t \in \delta t$ on a per-vehicle basis. When associating a sensor at location x_0 with a section δx, the underlying assumption is that on average, the traffic conditions at x_0 reflect those of the whole section δx, i.e. that traffic conditions are on average through time homogeneous on the section. This is not necessarily a bad assumption, as sections were often defined with this assumption in mind, but it must stated and kept in mind when involving FCDs.

To this average speed, any dispersion statistics is helpful to ask for: often associated with mean is the variance or its square-root, the standard deviation. Nevertheless, these are very sensitive to extremal values, or highly conditioned by the average speed algorithms at stake.

Asking for at least ranking statistics on the actual GPS speed data (i.e. instantaneous speeds) behind the averages provides more insight into the actual traffic dynamics, and allows the authority to better judge of the "relevance" of the aggregate indicators.

Another way can be to put alternative travel-time beacons on given corridors, that will act as a ground-truth against GPS FCD data, but financially impacting, and raises some mathematical issues.

Apparent discrepancies in distributions, that appear to break "natural" smoothness, have a good chance to result from some behind-the-scene deterministic process.

6.5.3 Final words on the Chapter

GPS receiver speed data is the first technology allowing widespread collection of the traffic state in the 100 years of traffic engineering. It samples through both time and space the speed of equipped vehicles. Traffic Management Centers face this breakthrough, mostly developed in private hands, with at first sight a very reduced array of tools. Nevertheless, this chapter shows that through the main instrument of interaction between the public and private worlds - tenders -, with the help of some simple descriptive statistics (distributions, time series, aggregate statistics, ranking), many of the advantages and shortfalls of the GPS FCD data can be highlighted. Not being behind the technical system collecting the data, like the TMCs were for the traffic sensors, doesn't mean they cannot acquire a deeper knowledge of it, be able to identify its flaws and exchange with the providers.

The shortfalls and "strange behaviors" discussed here show how algorithm and filtering decisions can radically transform the final rendering of the dataset, far from the original data, and more or less hidden when solely considering means or medians. Filtering must always be done consciously and the side effects of any of such process must be, as much as one can hope for, clearly analyzed.

The datasets of this chapter also introduce some of the fundamental questioning at stake in traffic engineering, to which only partial answers and assumptions could be given due to the lack of financially viable widespread observation techniques. Among the questions raised, it glanced at the definition of the areas of observation through time and space, and how it influences the resulting variables (speed, in the present case). Another aspect is the profound variability of the observed data, and the fact that GPS FCD allows to quantify it.

Chapter 7

GPS speed FCD: assessing speed-related policies

7.1 Introduction

As previously seen, the "speed", either spot-speed or journey-speed (or space-mean speed, the reciprocal of travel-time), has been of value both for the authority and for politicians[1].

The relations with speed today is ambiguous. On one hand, interurban expressways are still constructed to improve speed, and in urban areas, traffic-disruptive decisions are made while keeping an eye on the "network speedometer", like the *BRP* in Paris, in the hope that the decisions made will not impede too much the traffic conditions. The purpose is still to decrease the traffic volume while not degrading the network's performance. On the other hand, lowering speed-limits is seen as a tool for a safer road, a cleaner air, reduced noise, improved public space.

Besides the *BRP* speed to estimate speed, speeds on inner Paris arterials were also measured through the traditional spot-speed technique or by floating test-cars (until the 1990s for the latter). Today, speed estimates rely on both the *BRP* and spot-speed measures with tubes. GPS-based FCD provides a broad coverage of the road network and are not infrastructure dependent. They therefore provide speed information on broad areas, even a posteriori, whereas in the case of evaluating a lowered-speed policy, detectors have to be installed a priori.

This chapter presents the use of GPS-based FCD speed data to assess, in terms of speed, the evolution of traffic before-and-after the lowering of the speed-limit.

The first section draws a background on speed-limit reduction policies.

The second and third sections focus on before-and-after studies of GPS speed distributions. The second section is on urban and local streets, dealing with some inner-Paris 30 km.h^{-1} zones. The third section is an expressway-like corridor, dealing with the lowered speed-limit, from 80 to 70 km.h^{-1} of the Paris ringway. Note that these comparisons were done in 2015 with Provider 1 data, and that at the time the Author did not have the knowledge of its flaws, as shown by Chapter 6. Nonetheless, the dataset used is P1D1 (Provider 1 Dataset 1) which is as close to GPS raw data as the Provider 1 data got.

[1]In what follows, when reading "speed", the reader should understand "journey speed" or "space-mean speed", unless otherwise stated.

7.2 Background on speed-limit reduction policies

This section draws a quick background on speed-limit reduction policies. Reducing the speed-limit is very often a highly political decision, and can be a somewhat controversial measure. The decrease is justified with various road safety and environmental arguments.

7.2.1 Road safety

Vulnerable Road Users are defined by the European Commission as "non-motorised road users, such as pedestrians and cyclists as well as motor-cyclists and persons with disabilities or reduced mobility and orientation" [126]. Worldwide, they accounted for 50% of the road fatalities in 2010 [127], against 31% for car drivers, the 19% left not being categorized. In 2012, 28,000 died on the roads in Europe: pedestrians account for 21% of them, 25% are two-wheelers drivers (bicycles and motorcycles), 47% are car drivers [128]. In 2011, 61% of accidents occurred in urban environments, making 36% of the victims. Pedestrians are the main victims of these urban road accidents, representing 37% of those killed. In Paris, in 2011, 21.4% of accidents involving injury or death are linked to excessive speed [129].

The European Commission aims at halving the number of deaths on the roads during 2010-2020 period [130]. Among the means to reduce the death toll on roads, the European Parliament, in its September 27th, 2011 resolution on European road safety for the 2011-2020 period, "strongly recommends the responsible authorities to introduce speed-limits of 30 km/h in residential areas and on all one-lane roads in urban areas which have no separate cycle lane, with a view to protecting vulnerable road users more effectively" [131].

The literature on the relationship between driving speed and road crash rate relationship is numerous. An extensive literature review was published in 2006 [132]. One method compares, on a road section, its average speed and its crash rate. This yielded the Nilsson formulas [133]. Empirically based on a speed-limit change on Swedish roads, they link the crash rate variation with the average driving speed variation:

$$A_2 = A_1 \left(\frac{v_2}{v_1} \right)^{\alpha}$$

A_1 (respectively A_2) being the number of accidents during year 1 (resp. year 2, after lowering the speed-limit), and v_1 (resp. v_2) being the average driving speed during year 1 (resp. year 2). Under the assumption that the number of a serious accidents increased faster than the overall number of crashes as speed increased, Nilsson defined the α power coefficient to characterize the crash severity: $\alpha = 2$ for overall crashes, $\alpha = 3$ for severe injury crashes, and $\alpha = 4$ for fatal crashes. The reliability of these formulas has been confirmed [134], but is discussed for urban settings [135].

Another aspect of speed safety concerns is the pedestrian fatality risk. Rosen has carried out an extensive literature review on the "pedestrian fatality risk as a function of car impact speed" [136] (fig. 7.1).

7.2.2 Environmental aspects

Environmental aspects have a broad coverage: air and noise pollution, but also urban space overhauling.

Europe adopted in 2008 the "2020 climate and energy package" with the so-called "20-20-20 targets": "a 20% reduction in EU greenhouse gas emissions from 1990 levels, raising the share of

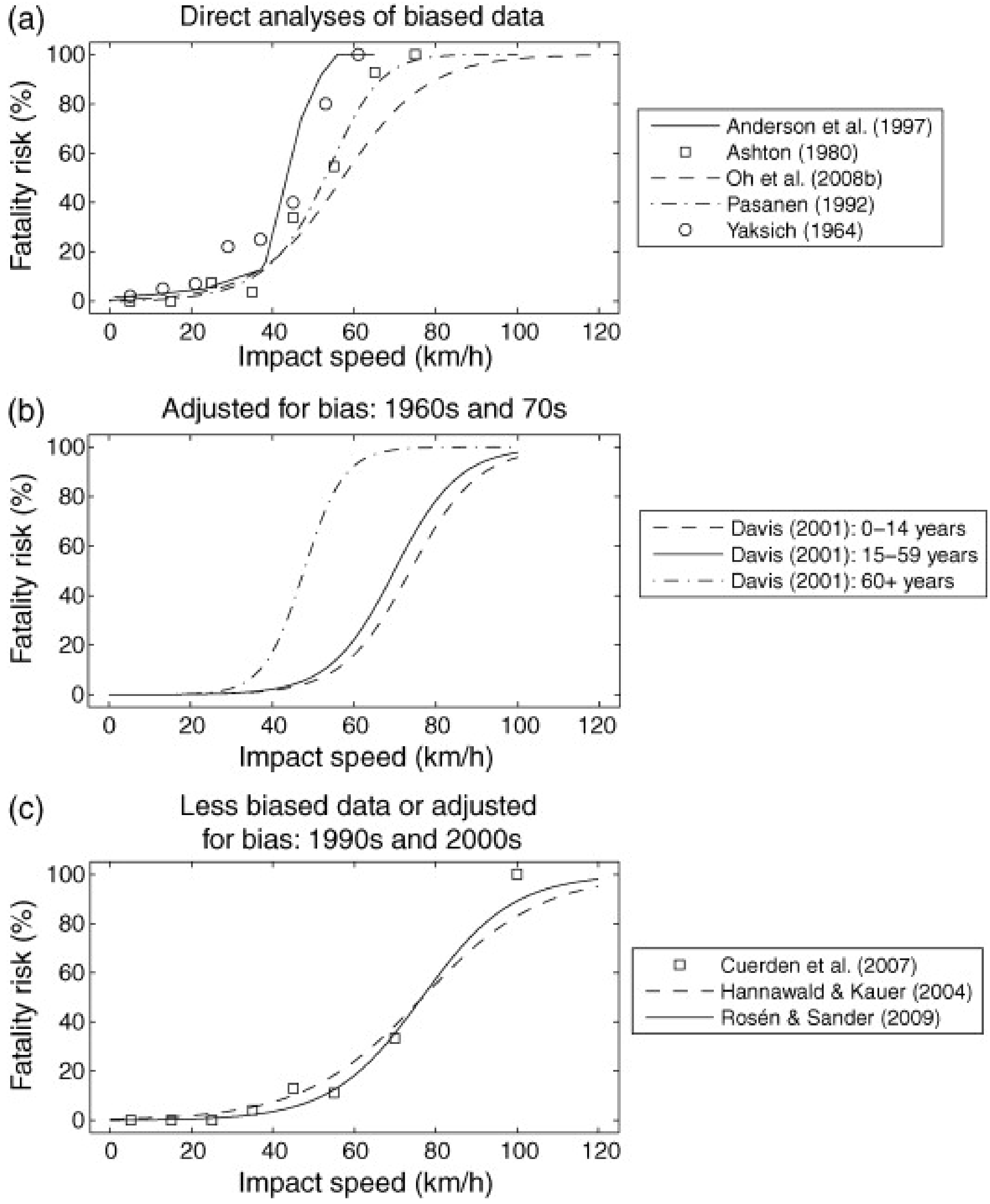

Figure 7.1 – Car impact speed = f(Fatality risk) ([136], p.28).

EU energy consumption produced from renewable resources to 20%, and a 20% improvement in the EU's energy efficiency" [137]. This package was extended in late 2014 by the "2030 framework for climate and energy policies" [138].

Limiting emissions is one of the justifications for the 30 km/h speed-limit. For the Ile-de-France region, in 2010, road transport accounted for 55% of NO_x emissions, of which 41% coming from private vehicles and 30% from lorries. Regarding greenhouse gases, road transport comes second at 27%, behind housing and service (42%). Among these 27%, private vehicles account for 57% of emissions [139].

Noise reduction is part of the European Commission environmental policies. The sound level of motor vehicles themselves has been under European supervision since Directive 70/157/EEC [140], updated under Directive 2007/34/EC [141]. This shows that road noise reduction has been under legal considerations since at least 1970. The current European legal framework is provided by Directive 2002/49/EC [142], both to identify noise levels and induce action both at the Union and Member States levels. The Directive defines *Environmental Noise* as "unwanted or harmful outdoor sound created by human activities, including noise emitted by means of transport, road traffic, rail traffic, air traffic, and from sites of industrial activity" [142]. Noise measurement methodologies are being harmonized. Under Directive 2015/996 [143], Member States should be using the same methods by late 2018 to assess noise from road, rail, air traffic and from industries.

Speed-limit reduction policies serve two main purposes: safety and the environment. Beyond the research aspects, these two fields are highly sensitive political topics. Strong empirical evidence has allowed to build models linking the driving speed with the crash fatality risk or the pedestrian fatality risk. The environmental aspects are also thoroughly investigated: energy consumption, noise and air pollution. Nonetheless, the expected improvements, especially for noise and air pollution, of lowering the speed are still not clearly shown and still debated.

7.3 Paris 30 km.h^{-1} zones

In the Summer of 2013, the City of Paris extended several 30 km.h^{-1} zones without any facility change (speed bumps, roadway narrowing, etc.) as used to be done for previous setups. The speed-limit change was simply signed with “Zone 30” signs at the zone boundaries.

The concerned inner Paris streets are not arterials and therefore not equipped with traffic sensors. No recent record of occasional counting campaigns in the zone could be found. Moreover, the City of Paris asked for assessment once the measure had been decided, and the time frame was too short for temporary spot-speed stations to be installed. Did the lowered speed-limit, without facility change, have an impact on driven speeds in the zone?

This section makes use GPS-based FCD instantaneous speed records to assess the speed distribution in the zone before and after the 30 km.h^{-1} speed-limit was posted. The dataset used is the First Dataset of Provider 1 (P1D1), and the periods compared are the business days of June 2013 (50 km.h^{-1} speed-limit) with those of June 2014 (30 km.h^{-1} speed-limit). The study is carried out over the Télégraphe 30 km.h^{-1} zone, the biggest area of the Summer 2013 extension campaign, which Figure 7.2 locates in the Northeastern side of Paris. The zone only includes local street, and does not include its boundary arterials, which retained their 50 km.h^{-1} speed-limit. It represents a cumulative distance of 7 km of oriented links.

At first, a main concern is raised: is there enough GPS data available to carry out the study?

Then, speed distributions are compared to answer the consequences of the speed-limit on driven speeds.

7.3.1 The GPS data availability in the zone

Given the low levels of traffic anticipated in the local streets studied, GPS data availability is key. Such availability is checked through counting N_{GPS}, the number of GPS records collected in the zone. No traffic counting campaign was carried within the studied periods and zone, and therefore no comparison can be performed on that aspect.

Associated to the number of GPS records N_{GPS} is the linear density of records λ_{GPS} over a

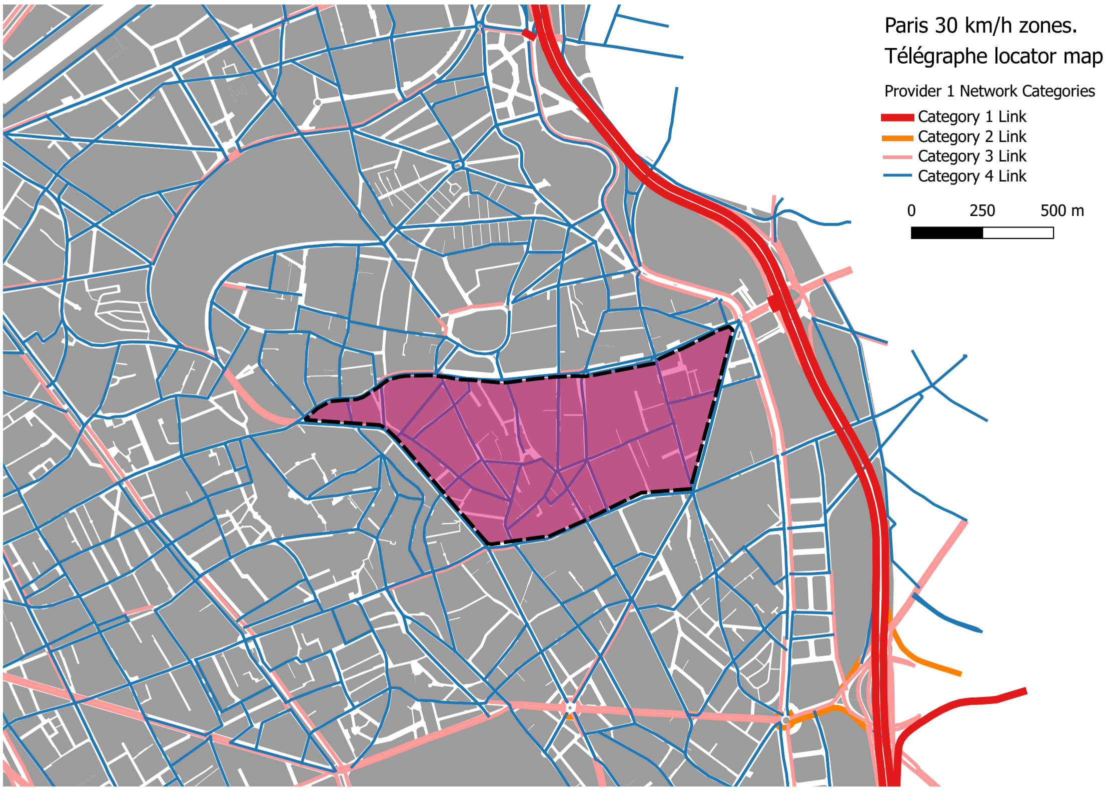

Figure 7.2 – Locator Map of the studied Télégraphe 30 km.h^{-1} zone upon the Provider 1 network.

network of length L (in messages per kilometers, msg.km^{-1}):

$$\lambda_{GPS} = \frac{N_{GPS}}{L} \tag{7.3.1}$$

Among other figures, Table 7.1 shows the count, N_{GPS}, of GPS records over the zone. As previously done and explained, the GPS instantaneous speed V_{GPS} distribution is split into two modes, stopped ($V_{GPS} < 5$ km.h^{-1}) and running ($V_{GPS} \geqslant 5$ km.h^{-1}). The plot of the distribution, done in Figure 7.4, supports this view. Between 2013 and 2014, there is a 2 % increase in the total count (all modes), from a linear density of $\lambda_{GPS} = 64,840$ msg.km^{-1} in 2013 to $\lambda_{GPS} = 66,424$ msg.km^{-1} in 2014, but the stopped mode contributes much more than the running mode to the rise, the stopped-running mix nonetheless staying balanced.

The densities presented as such assume that the information is uniformly spread across the zone, which in reality may not be the case. Nonetheless, the question remains how speed distributions evolve with speed-limit change. It can be reasonably assumed that the density on each segment is somehow an increasing function of the traffic volume. Assessing speed distributions in a zone, with more trafficked streets weighing more than less trafficked streets, is coherent, even more when remembering that traffic volume is a key variable in traffic safety.

Over a month period, the data availability is satisfactory, either when considering all modes or just the running mode.

Another assumption is made here: since the speed distribution is studied in relation with the speed-limit, the study focuses on the running mode. Speeds reported below 5 km.h^{-1} can reasonably be associated with maneuvering vehicles (yielding or stopping at an intersection, parking, etc.).

For illustration purposes, but also in order to better understand the time variations of GPS

Dataset	Mode	Period (bus. days)	Count N_{GPS}	Linear density λ_{GPS}	25th p.	50th p.	75th p.	average	st. dev.	IQR
P1D1	running	June 2013	227,457	32,494	13	22	30	22	11	17
P1D1	running	June 2014	228,031	32,576	14	22	30	23	12	16
P1D1	stopped	June 2013	226,426	32,347	0	0	0	0	1	0
P1D1	stopped	June 2014	236,936	33,848	0	0	0	0	1	0
P1D1	all	June 2013	453,883	64,840	0	5	22	11	14	22
P1D1	all	June 2014	464,967	66,424	0	3	22	11	14	22

Table 7.1 – Descriptive statistics by mode (stopped or running) and period (Business days of June 2013, and June 2014) of the instantaneous speeds of the Provider 1 Delivery 1 dataset (P1D1) over the Télégraphe zone.

traffic within the zone, Figure 7.3 shows the hourly variation of the distribution of N_{GPS} for the running mode. No real trend can be identified, except that the level of information "increases" during the day (with greater variability) than during the night. The trend remains stable, with a median between 400 and 450 messages per hour of day. This is still a satisfactory level of data.

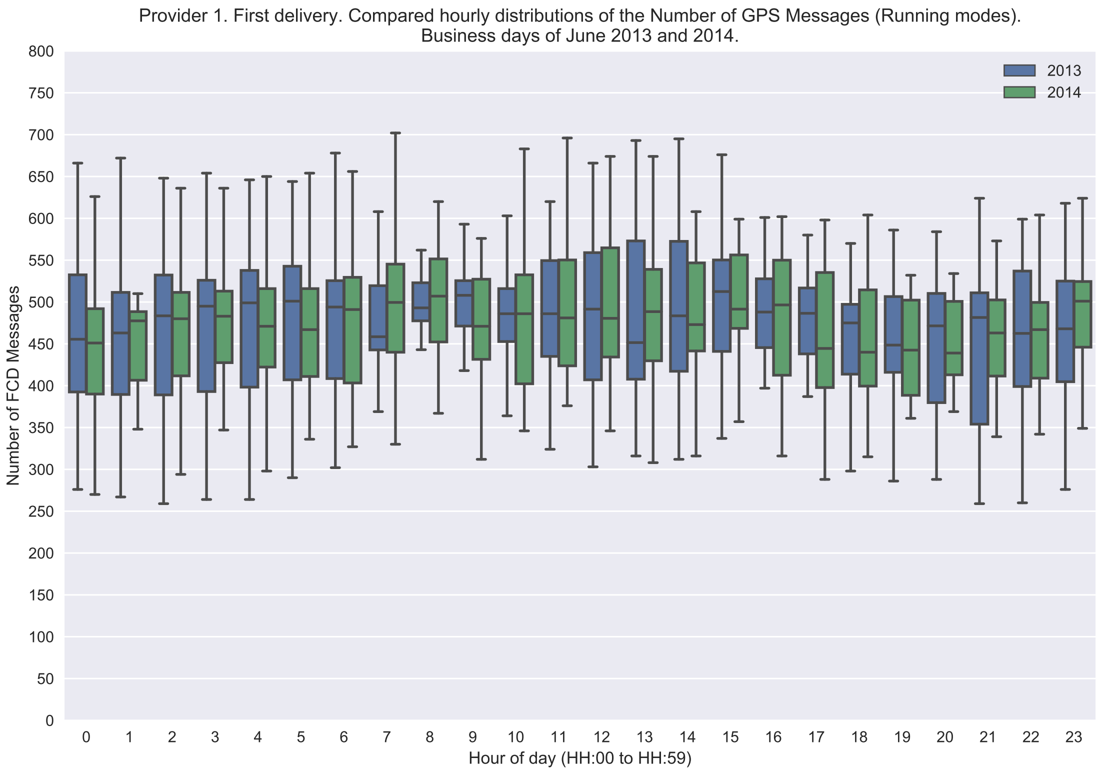

Figure 7.3 – P1D1 dataset. Number of messages M_{GPS} per hour h. Compared hourly distributions, for the running mode. June 2013 and June 2014, business days.

7.3.2 Comparing speed distributions

The availability having been empirically shown as satisfactory, the speed distributions before and after the lowered speed-limit can be carried out. As mentioned in the previous section, the comparison will essentially focus on the running mode.

The all-mode distribution of instantaneous speeds is plotted on Figure 7.4, which shows the importance of zero speeds in the dataset, and the pertinence of the bimodal analysis even on local streets. Figure 7.5 shows the running mode: the distribution is spread, with no clear shape appearing for the 5-25 speed range, and showing a gradual decrease for speeds above 25 km.h^{-1}. It can already be hinted from the running mode speed distribution that the speed-limit change had little to no effect on the speed distribution.

A look at time variations, as done on Figure 7.6, shows that the median speed and the spread of distribution of speeds stays constant before and after the speed-limit change. Moreover, the speed distribution is almost time-independent. Global figures on Table 7.1 confirm the lack of difference both in terms of central tendancy (almost-constant median and average) and variability (almost-constant standard deviation and inter-quartile range). In fact, most running speeds were already under 30 km.h^{-1} even before the measure was implemented: the 75th speed percentile is at 30 km.h^{-1} for the running mode, and at 22 when considering all modes.

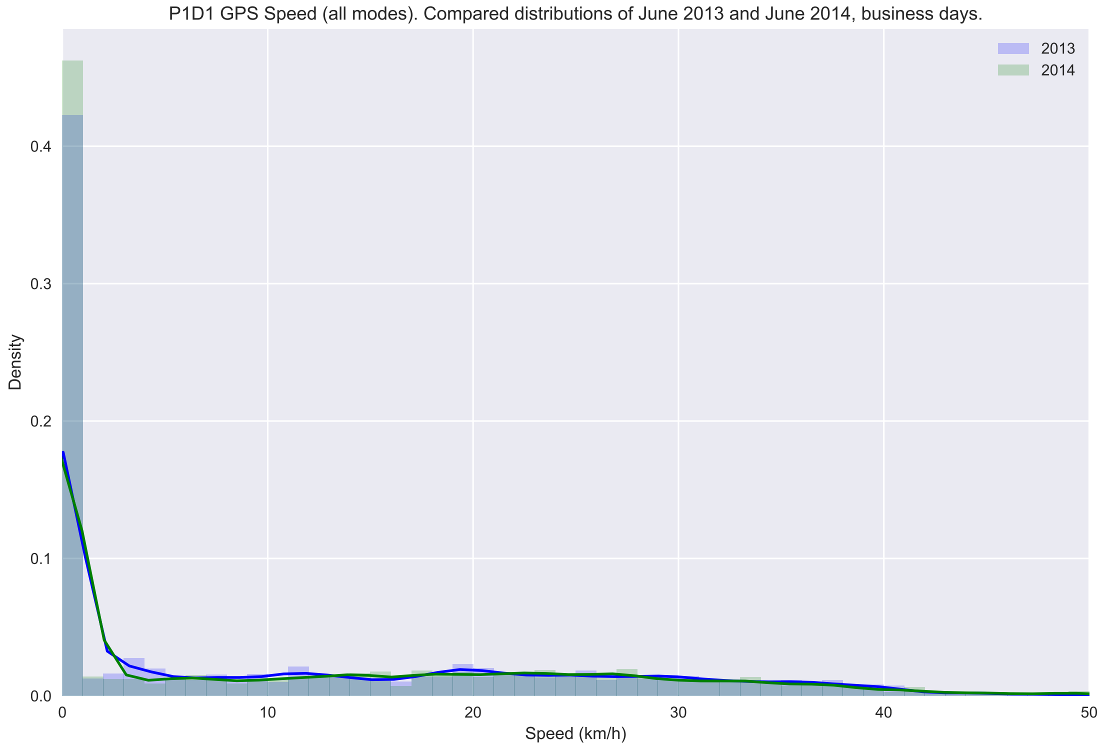

Figure 7.4 – P1D1 GPS Instantaneous Speed. Compared distributions, for all modes. June 2013 and June 2014, business days.

GPS speed datasets are well suited for the assessment of speed-related policies.

Even on local streets, the availability of GPS speed data for off-line analysis remains satisfactory, with the help of two aspects: using both the space (a zone of several streets) and time (a month period) depth of coverage offered by off-line datasets. The computation of a linear density of data is a helpful tool to assess the effective coverage.

The comparison of the GPS instantaneous speed distribution before and after the speed-limit change shows the measure had little to no effect on the speed of vehicles. In fact, the speed distribution was already mostly below the 30 km.h^{-1} speed-limit before it was officially lowered, both when considering all modes or simply the running mode. This, in a way, shows that for the most part, drivers adapt their speed to the local setting. Moreover, it may be hinted that a behavior change with these low speeds is not triggered by a speed-limit change, as the last quartile of speed records is still above 30 km.h^{-1} after the speed-limit change.

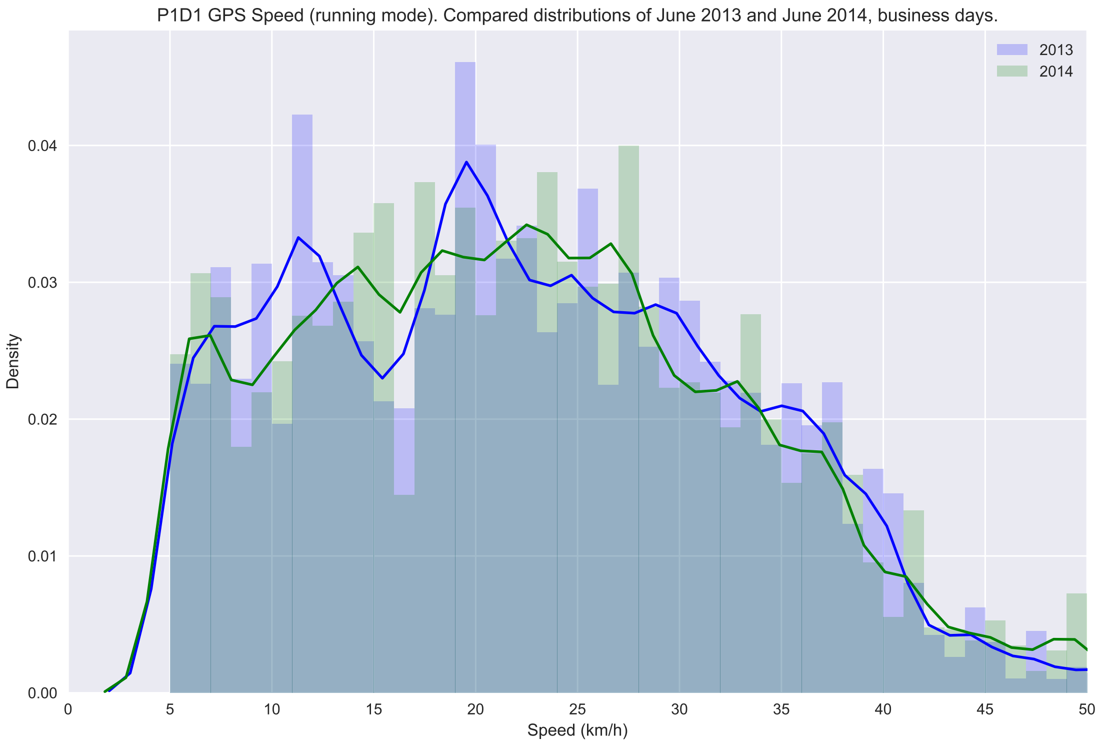

Figure 7.5 – P1D1 GPS Instantaneous Speed. Compared distributions, for all modes. June 2013 and June 2014, business days.

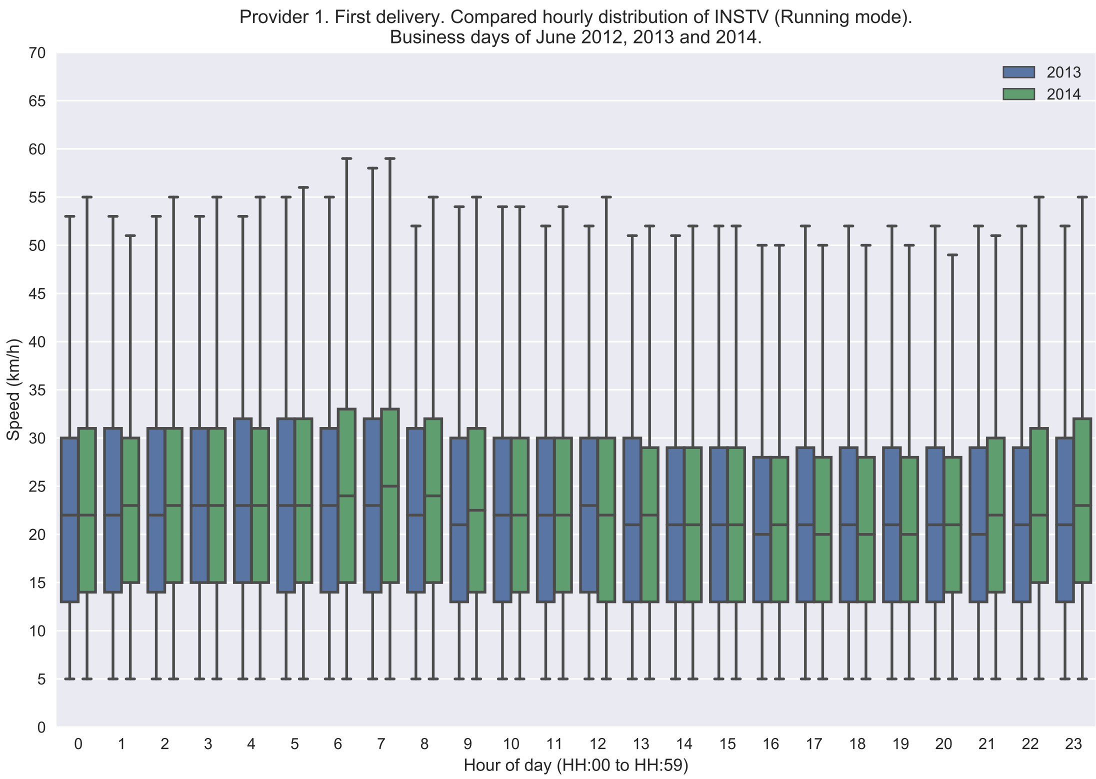

Figure 7.6 – P1D1 GPS Instantaneous Speed. Compared hourly distributions, for the running mode. June 2013 and June 2014, business days.

7.4 Ringway at 70

Paris ringway is a peculiar road. It is Paris region innermost ringway, around 35 km long, and shares many characteristics with standard expressways, being a divided highway with two to five lanes per way, and having grade-separated, traffic lights free interchanges. It connects seven radial motorways, that serve both local and interurban traffic.

The first of its peculiarities is its status: it is property of and managed by the City of Paris, making it the busiest municipal road in France, and has a dedicated State Police brigade. It is not designated as an expressway or as a motorway, but as a "Boulevard". The main roadway does not have priority over the access ramps, but must give way on the right to entering traffic. This priority regime is compatible with the fact that there are no acceleration lanes and very short merges for the entrance ramps.

At its completion in April 1973, its speed-limit was explicitly set by the French traffic code at 80 km.h^{-1}.

As shown by section 7.2, lowering speed has become one of the main political mean of action against traffic nuisances. Gradually, the connecting radial motorways have seen there speeds lowered to 70 km.h^{-1} on their approach to Paris. This constituted an additional motivation to lower the speed on the ringway.

On January 10th, 2014, the speed-limit was lowered to 70 km.h^{-1}. The decision immediately triggered heated reactions by some politicians and generally pro-motoring organizations. Great political scrutiny was given to the months that followed, regarding the infrastructure performance (did the lowered speed effectively reduce congestion and allowed more traffic to pass by?) and safety (reduction in accidents and severity?). The lowered speed was accompanied by the installation of additional automatic speed cameras to enforce the speed-limit.

The Author looked into the infrastructure performance issue, with FCD data at hand, used the case to compare the answers given by the legacy indicators based on the ringway traffic loops infrastructure, and the one given by GPS speed distributions.

The first subsection presents the ringway's legacy traffic data collection system and associated indicators, and the results they provide. The second subsection focuses on the GPS speed. The third subsection looks into the average speed question between dual-loop and GPS FCD measurements.

7.4.1 Traffic data collection and associated indicators on the ringway

The ringway is managed by its own Traffic Management Center and related system, known as IPER-REPER and independent of the SURF system.

Traffic data is collected by traffic stations all based inductive loops technology, with one loop per traffic lane installed in one row. Per roadway, i.e. inner or outer ring, there are 72 traffic stations. Flow Q and occupancy O is measured by all 72 stations. Every one out of five stations, i.e. 13 stations per roadway, measures speed: these stations are fitted with a double row of loops. This means flow and occupancy are measured roughly every 500 m, and speed every 2,500 m.

The acquisition time interval is 20 s long.

For each 20 second interval, flow is defined as the number of rising edges. Speed is computed as the time difference between the rising edges of the two rows of loops, the downstream row being taken as the reference and knowing the distance between the two rows of loops.

The raw electronic data is then transformed into valid $(Q, K, V)_{20s}$:

- $Q_{20s} = \frac{Q_{20s,\text{raw}}}{n \times \frac{0.01}{3600}}$

- $K_{20s} = \frac{K_{20s,\text{raw}}}{\frac{n}{3}} \times 100$
- $V_{20s} = \frac{\frac{3}{1000} \times Q_{20s,\text{raw}}}{TTe_{20s,\text{raw}} \times \frac{0.01}{3600}}$
- $V_{20s} = 0$ if $TTe_{20s,\text{raw}} = 0$.

The data is then temporally aggregated over n timeslots, for each sensor (i.e. each traffic lane):

- $Q_{agreg} = \frac{\sum_{i=1}^{i=n} Q_i}{n}$
- $K_{agreg} = \frac{\sum_{i=1}^{i=n} K_i}{n}$
- $V_{agreg} = \frac{\sum_{i=1}^{i=n} Q_i}{\sum_{i=1}^{i=n} \frac{Q_i}{V_i}}$
- $V_{agreg} = 0$ if $V_i = 0$.

The data can then be aggregated spatially over the L traffic lanes of the station S:

- $Q_S = \sum_{j=1}^{j=L} Q_j$
- $K_S = \sum_{j=1}^{j=L} K_j$
- $V_{agreg} = \frac{\sum_{j=1}^{j=L} Q_j}{\sum_{j=1}^{j=L} \frac{Q_j}{V_j}}$

Traffic stations S_{single} not measuring the speed (single row of loops) are associated with a given two-row traffic station S_{double} that measures a speed V_{double}. A speed V_{single} is then analytically derived from V_double.

S_{double} yields an electrical length $l_e = \dfrac{10 \times O_{double} \times V_{double} \times n_{double}}{Q_{double}}$, n being the number of lanes, i.e., traffic loops.

The speed V_{single} then is:

$$V_{single} = \frac{Q_{single} \times l_e}{(10 \times O_{single} \times n_{single})} \tag{7.4.1}$$

Like for the SURF-managed road network, in the IPER-REPER system, the ringway is modeled as an oriented graph. Each traffic station is associated with a link i of length L_i. For a given time t, which is the end of a time interval $[t - \Delta t, t]$, a link i bears an occupancy $O_i(t)$, a flow $Q_i(t)$ and a speed $V_i(t)$. A corridor on the ringway is, like for SURF, defined as a continuous and finite set of links i, and of total length $L = \sum_i L_i$.

Two indicators can then be computed for the ringway, based on the loops data, and very much in homology with the SURF indicators.

The first indicator is the Vehicle Kilometers Traveled (VKT_i), defined for a link i and a time t as:

$$VKT_i = Q_i \cdot L_i \tag{7.4.2}$$

The VKT defined over a corridor (set of links i) and for a time t:

$$VKT = \sum_i VKT_i = \sum_i Q_i \cdot L_i \tag{7.4.3}$$

The Normalized VKT, VKT_{norm}, then is, over a corridor of length L:

$$VKT_{norm} = \frac{VKT}{L} \tag{7.4.4}$$

The second indicator is the time spent TS_i, defined for a link i and a time t as:

$$\begin{aligned} TS_i &= \frac{Q_i L_i}{V_i} \text{ if } V_i > 0 \\ TS_i &= TS_{max}(T_i) \text{ if } V_i = 0 \end{aligned} \tag{7.4.5}$$

The time spent TS for a corridor (set of links i) and for a time t then is:

$$TS = \sum_i TS_i \tag{7.4.6}$$

The average speed indicator $\overline{V}$ for a corridor (set of links i) and for a time t then is:

$$\overline{V} = \frac{VKT}{TS} \tag{7.4.7}$$

The variations of the indicators are interpreted the same way as their $TPIM$ counterparts, and as described in Table 2.2.

The time-series, averaged by 15 min time-slots, of the normalized VKT_{norm} is plotted on Figure 7.7, and the average speed $\overline{V}$ on Figure 7.8.

The general shape of the curves speaks for itself, and stays the same for the three compared periods. Traffic conditions are “at their best” during the night (21:00 to 05:00) with a decreasing demand and a stable speed at its highest. During the day, the volume roughly plateaus whereas the speed variations clearly show the morning (06:00-10:00) and evening peaks (15:00-20:00), with the mid-day period being intermediate between the night “free-flow” and the peak “jam”.

Figure 7.9 plots on an adimensional unit scale both VKT_{norm} and $\overline{V}$ for June 2012, 2013 and 2014. Plotted is X' transformed from X as follows:

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{7.4.8}$$

Speed is at its highest during the night, between 22:00 and 06:00 the following morning, while VKT drops until 04:00, and starts to increase again between 04:00 and 05:00. Traffic volume has a notable effect on speed starting at 06:00 when it reaches 0.6 units. Until 07:00, there is an increasing demand: the volume sharply peaks at 07:00, reaching its day-high value, whereas the speed keeps decreasing. After 07:00, the volume decreases as the speed continues to drop, reaching its morning-low at 09:00: over this period, it is a decrease in supply more than in demand. After 09:00, both the speed and the demand increase again, until noon: there is an increase in supply according to Table 2.2, but certainly along a decrease in demand as the morning peak has ended. From 12:00 to 15:00, the volume roughly stays constant, whereas the speed gradually decreases, translating an increase in demand. Past 15:00 until 18:00, the volume keeps decreasing as well as the speed, as supply decreases due to congestion. The evening peak lowest is reached at 18:00 for the speed, and the volume is also at its lowest for the 07:00-21:00 period. Past 18:00, the speed increases as well as the volume: this is an increase in supply. The volume peaks again at 20:00 whereas the speed keeps increasing. The volume decreases past 20:00 until the end of the day, while the speed increases and stabilizes at 22:00 at its highest: decrease in demand.

The compared VKT_{norm} time series of June 2012 and June 2013 volumes (with a speed-limit of 80 km.h^{-1}), with June 2014 (with a speed-limit of 70 km.h^{-1}), shows no clear differences before and after the speed-limit implementation in terms of volume. Likewise, when considering the speed time series, the only clear impact shown by the speed-limit is seen between 22:00 and 06:00. It only shows that in free-flow conditions, the free-flow speed is oscillating between 60 and 70 instead of being between 70 and 80 before. The difference between June 2012 and June 2013 can be explained by the additional automatic speed cameras, which dramatically reduced speeding, especially at night.

The compared general tendency of $(VKT_{norm}, \overline{V})$ for the three years shows the same tendencies at the same times of day, with slight variations that cannot be associated with any clear reason. Note the min-max range of $\overline{V}$ for 2014 is lower than for 2012 and 2013, hence the more pronounced "bump" between 10:00 and 13:00 in the adimensional plot, whereas in absolute value, it remains in the same range of values as 2012 and 2013.

In the end, the indicators show that the speed-limit change induced no macroscopically perceptible change in the volume carried by the ringway. Nonetheless, at night-time, from 22:00 to 06:00, the average speed-limit, or "free-flow speed-limit" given the traffic conditions, reflects the regulatory measures: from 2012 to 2013 (speed-limit 80 km.h^{-1}), an increase in the number of speed radars shows a decrease in the average speed which then abide by the speed-limit; from 2013 to 2014, the average speed drops to abide by the new limit of 70 km.h^{-1}.

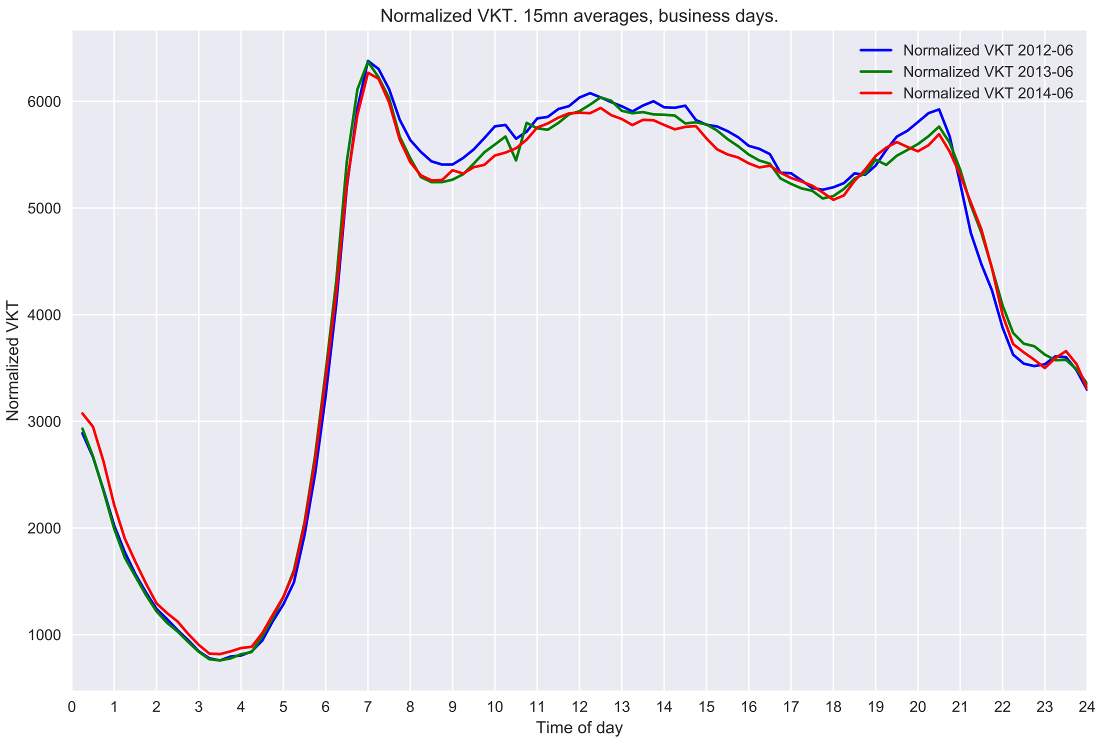

Figure 7.7 – Normalized VKT over Paris ringway. 15 mn averages, business days.

7.4.2 Comparing GPS speed distributions

The indicators taken over the whole ringway show no clear effect of the speed-limit change on the ringway traffic dynamics, except at night for the free-flow speed. Nonetheless, these indicators rely on spot measures, whereas the GPS fleet randomly samples the whole ringway both through time and space, each receiver emitting on a fixed time basis. The dataset used by the Author is the First Delivery of the First Provider (P1D1), on the ringway mainline (the ramps and interchanges are excluded). Of course, given the precision of the GPS positioning and of the map-matching process, hardly quantifiable side-effects must be mentioned: vehicles traveling on local side roads parallel to or passing over or under the ringway may get caught, as well as vehicles traveling on exit or entrance ramp, which will have speed regimes different from those on the mainline. Moreover, unlike the traffic sensors which catch vehicles on travel lanes, and away from ramps merge and diverge, each GPS vehicle emits whatever his location, including exiting or entering the ringway. With this in mind, the Author assumes that the global

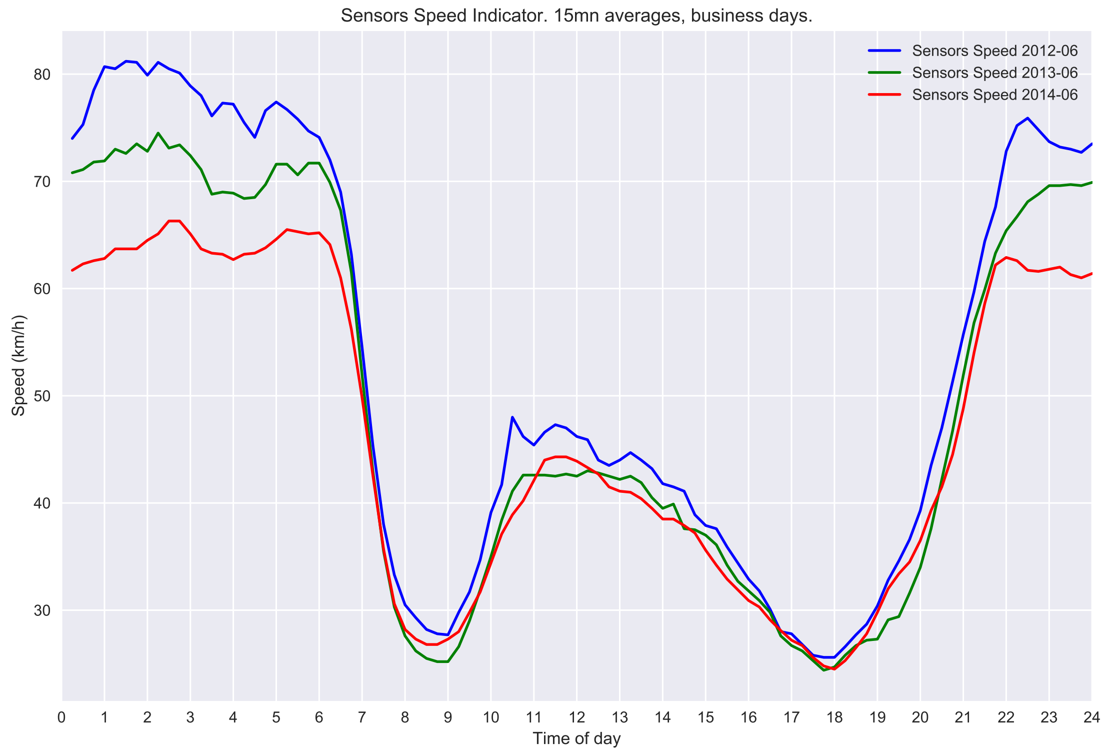

Figure 7.8 – Sensors speed over Paris ringway. 15 mn averages, business days.

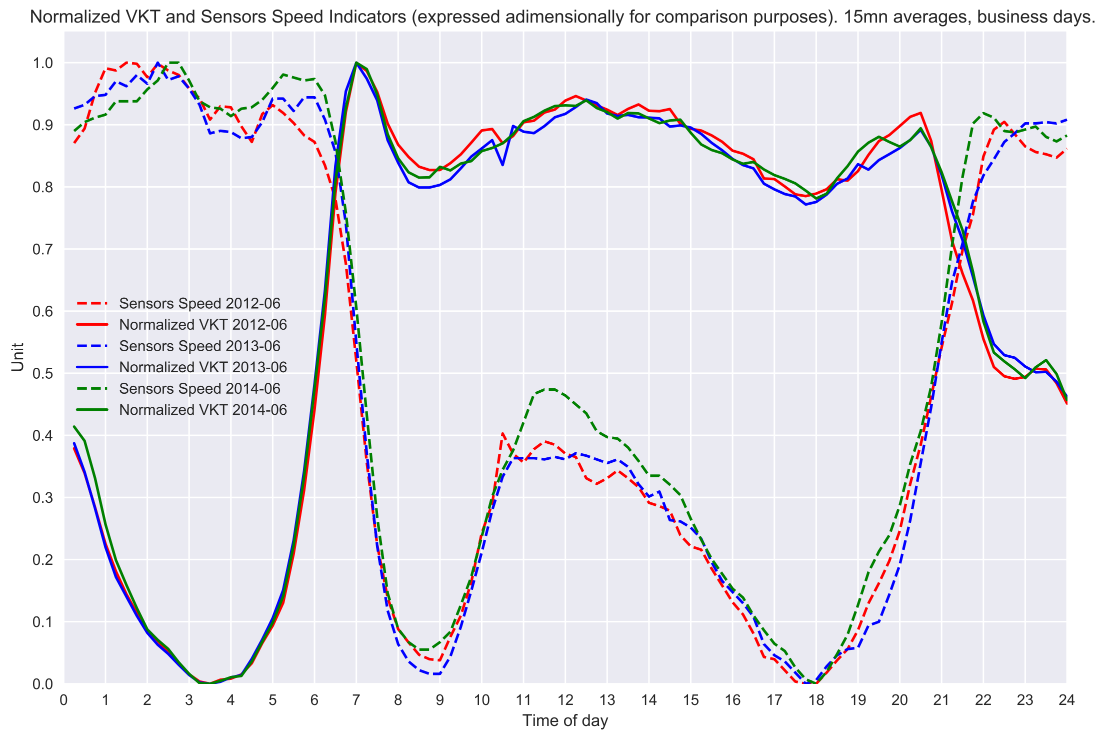

Figure 7.9 – Normalized VKT and sensor speed indicators over Paris ringway, expressed adimensionally for comparison purposes. 15 mn averages, business days of June 2012.

volume of traffic, and hence of speed records on the ringway mainline, will overweight these side effects when considering the speed distributions over relatively long periods $\tau \gg \Delta t$.

Each speed record is an instantaneous speed value. They are logged by fixed time-intervals of Δt which are section dependent. For the ringway, the time basis was the same for all sections ($\Delta t = 3$ min) as all were in category 1. The analysis focuses on the distribution of these speeds over the whole ringway mainline.

In the line of Chapter 6, the instantaneous speed v apparent bimodal distribution is split into a stopped ($v < 5$ km.h^{-1}) and a running mode ($v \geqslant 5$ km.h^{-1}). The compared periods are the business days of June 2012, June 2013 and June 2014.

Figure 7.10 gives the distribution of instantaneous speeds for all modes.

Focusing on the running mode, Figure 7.11 shows the overall distribution of this mode. It is itself bimodal, making the instantaneous speed distribution trimodal. A first mode appears to dominate for speed values between 5 and 40 km.h^{-1}. A second mode dominates for speeds above 40, peaking near the speed-limit. The first mode acts as a tail to the second mode: the first mode is the witness of congested traffic, whereas the second mode is the free-flowing traffic, the mix of these two regimes making up the distribution of the running mode. Jammed traffic, or stopped mode, makes up the third mode.

A first consequence of the speed-limit change to be seen is that it concentrates its effect on the second free-flowing traffic mode, leaving the congested traffic mode largely untouched.

As seen in Chapter 6, the 2014 distribution shows artefacts that are not to be seen in previous years (2012 and 2013), with a deterministic peak at 77 and 88 km.h^{-1}. This is caused by a loss of signal by the receiver, and not updated map which still considers in June 2014, sections of the ringway with the former speed-limit. The correction through a first-degree polynomial approximation of the aberrant values: the 77 density is approximated by linear interpolation from the 76 and 78 speed values density, and likewise the 88 by the 87 and 89. The "corrected" dataset (referred to as P1D1C) is used in subsequent analysis, Figure 7.12 showing the distribution of the running mode.

Table 7.2 gives the aggregate statistics of the distribution either split by modes and as a whole, for the three periods, and with and without the peak correction for the June 2014 dataset. Overall, the number of records increases drastically between June 2012 and June 2014, from circa 16.5 million records to over 21.5 million. Nonetheless, the split between stopped and running mode is roughly constant in terms of percentage: for 2012, 88 % of records for the running mode, in 2013, 92 %, and in 2014, 91 %. The median speed gradually drops (from 62 to 60 km.h^{-1}), whereas the 25th percentile stays constant between 2012 and 2014 (except in 2013 for a reason the Author could not explain). The 75th percentile drops between 2012-2013 and 2014, as a direct consequence of the speed-limit change. Like the median, the arithmetic average does not change due to the speed-limit (it is equal to its 2013 value), but the standard deviation drops between the 2012-2013 and 2014 periods. The same can be said of the inter-quartile range which sees a sharp drop. In the end, this first global analysis shows that the median and average speeds remain unchanged by the lowered speed-limit, but that the speed distribution dispersion has been significantly reduced.

The hourly distribution of instantaneous speeds is summarized by Figure 7.13, with a boxplot representing each hour. The first notable aspect is the much higher dispersion of speed values during the day (07:00 to 21:00) than at night (21:00 to 07:00). This is a somehow expected translation of the heavy traffic during the day, as previously shown by the loop-based indicators. The situation eases somehow between 10:00 and 13:00 with a lower dispersion. In other words, the lower the median speed, the heavier the traffic and more dispersion of speed values. Again, the effect of the speed-limit change can only be seen clearly during the night free-flow period, with a 2014 median speed circa 10 km.h^{-1} below the 2012 and 2013 one. The boxes whiskers cover a distance of 1.5 times the inter-quartile range, and thus shows the extent of most values

Dataset	Mode	Period (bus. days)	Count	25th p.	50th p.	75th p.	average	st. dev.	IQR
P1D1	running	June 2012	14,581,996	37	62	75	57	25	38
P1D1	running	June 2013	17,803,460	33	60	75	54	25	42
P1D1	running	June 2014	19,792,983	37	59	70	54	23	33
P1D1C	running	June 2014	19,126,867	36	59	69	53	22	33
P1D1	stopped	June 2012	1,884,398	0	0	0	0	1	0
P1D1	stopped	June 2013	1,478,488	0	0	0	0	1	0
P1D1	stopped	June 2014	1,839,713	0	0	0	0	1	0
P1D1C	stopped	June 2014	1,839,713	0	0	0	0	1	0
P1D1	all	June 2012	16,466,394	26	57	74	50	29	48
P1D1	all	June 2013	19,281,948	26	56	74	50	28	48
P1D1	all	June 2014	21,632,696	28	57	69	49	26	41
P1D1C	all	June 2014	20,966,580	27	55	68	48	26	41

Table 7.2 – Descriptive statistics by mode (stopped or running) and period (Business days of June 2012, June 2013, and June 2014) of the instantaneous speeds of the Provider 1 Delivery 1 dataset (P1D1), and for the June 2014 period with the peak correction (P1D1C).

outside this range (the outliers are not plotted). Values outside the range are the result of two facts: speeding vehicles, and aberrant values (result of various technical faults, as illustrated previously). Even the additional speed radars does not mean that no car speeds beyond the speed-limit: the radars only do spot controls, but do not control stretches of road.

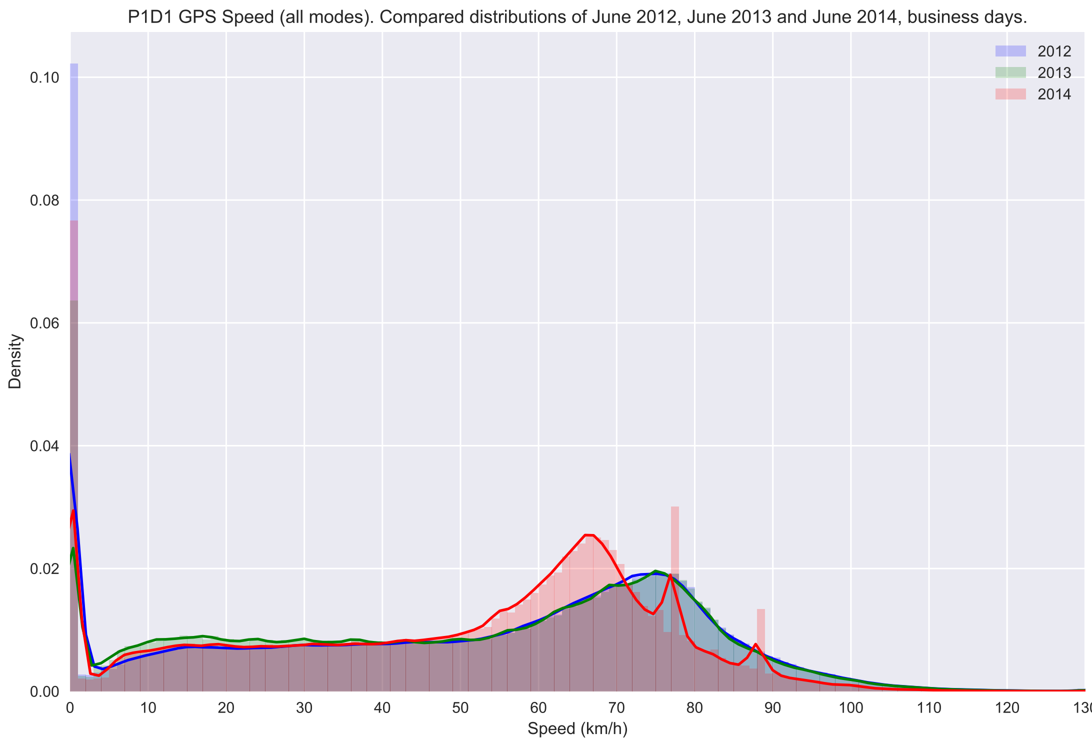

Figure 7.10 – Provider 1. First delivery. Compared distributions of instantaneous speeds (all modes). Business days of June 2012, June 2013, June 2014.

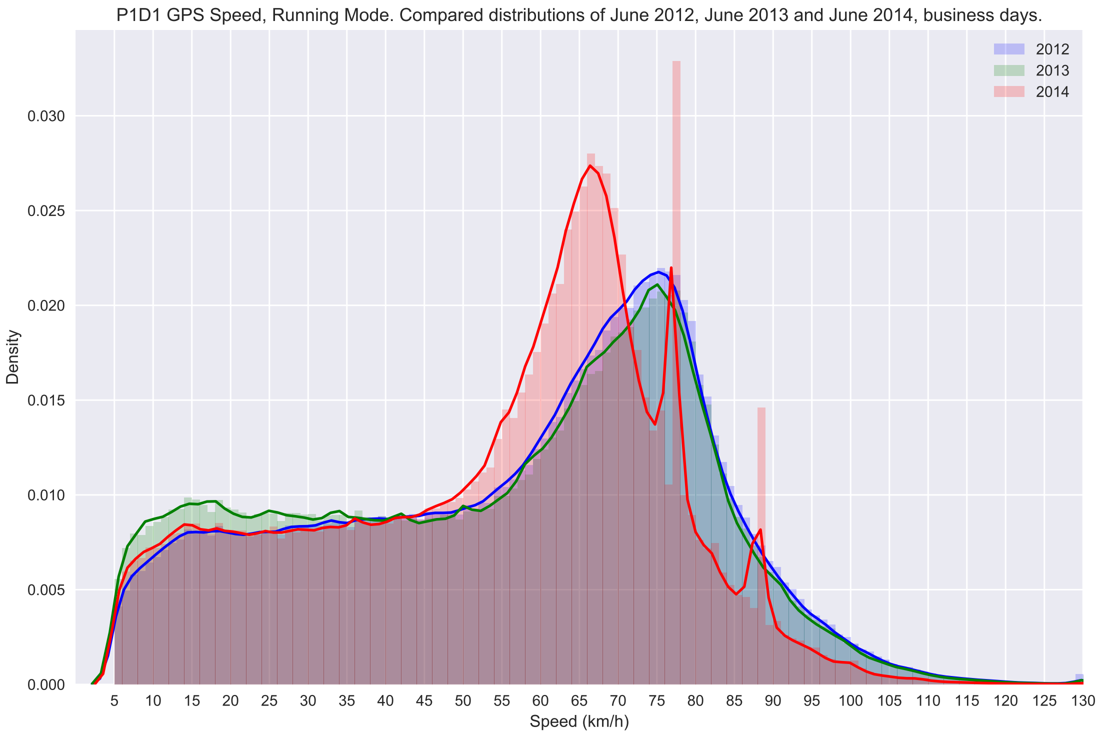

Figure 7.11 – Provider 1. First delivery (P1D1). Compared distributions of instantaneous speeds (running mode). Business days of June 2012, June 2013, June 2014.

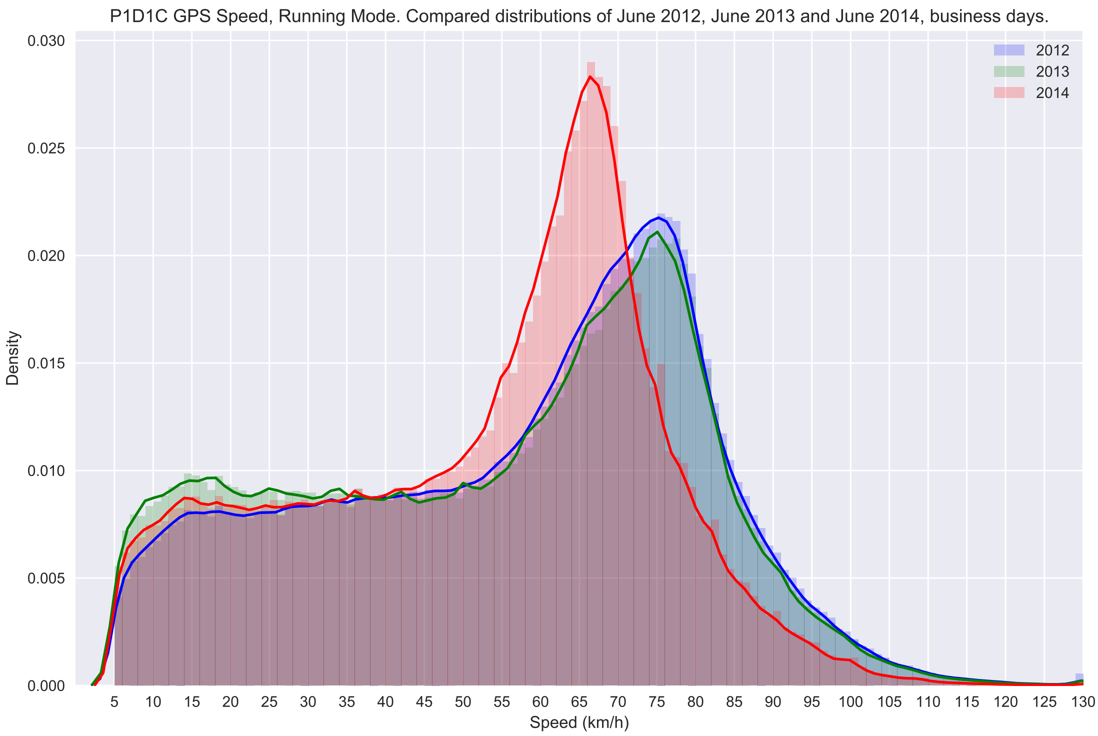

Figure 7.12 – Provider 1. First delivery (P1D1C). Compared distributions of instantaneous speeds (running mode). Business days of June 2012, June 2013, June 2014.

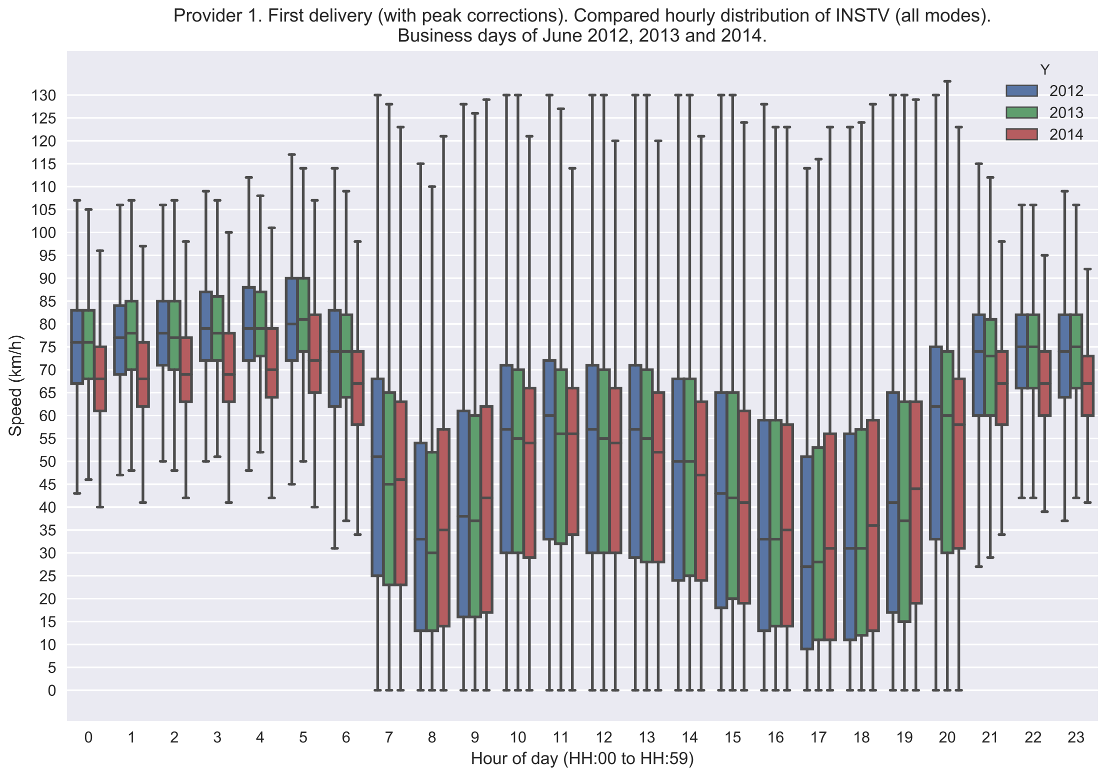

Figure 7.13 – Provider 1. First delivery. Compared hourly distribution of instantaneous speeds (all modes, P1D1C dataset). Business days of June 2012, June 2013, June 2014.

7.4.3 Loops and GPS speeds: a question of averages

The temptation to compare GPS speeds with loops speed is great, nonetheless, much care must be taken in doing so.

Loops speed is an average taken over a period of time Δt, and results in timing the passage of individual vehicles between two point separated by a known distance. This time-average speed is then transformed into a space-average speed $\overline{V_{LOOPS}}$ by computing its harmonic mean. In Paris algorithm, the harmonic mean is weighted by the flow. The justification behind this was the subsequent computation of travel-times: the links associated with each traffic station would all "weight the same" if flow was not considered. The Author here considers the traffic data as stored in the IPER-REPER database, from the double-loop traffic stations. Given the data treatments, the "loops speed" saved in the database is in fact already turned into a space-mean speed. The purpose here is to compare the central tendency of the average speeds measured the dual loops, i.e. $\overline{V_{loops}}$, based on the IPER-REPER database data will directly be the arithmetic average of the $V_i(t)$ stored for each link i and section timestamp t equipped with a double-loop traffic station:

$$\overline{V_{LOOPS}} = \overline{V_i(t)} \tag{7.4.9}$$

GPS speeds are instantaneous speeds computed by the receiver seconds before it emits its raw record to its company's server. On a link between $x = 0$ and $x = \Delta x$, during a period of time Δt, N_{GPS} vehicles j will pass and send a total M_{GPS} records, all including an instantaneous speed value. As stated before, these vehicles will sample the link both through time and space: each vehicle j will emit speed values $V_j(t, x)$, with $t \times x \in [0, \Delta t] \times [0, \Delta x]$. Considering the "instantaneous" characteristic of GPS speeds, and the fact that space was sampled as well as time, the Author decided to take the arithmetic average of the $V_j(t, x)$ to define the average GPS speed $\overline{V_{GPS}}$:

$$\overline{V_{GPS}}(\Delta t, \Delta x) = \frac{1}{M_{GPS}} \sum_{t,x} V_j(t, x) \tag{7.4.10}$$

This joins EDIE's definition considering that we are in a short time–long roadway perspective. EDIE's generalized definition of space-mean speed, as the ratio of the aggregate distance traveled by the aggregate time spent, would be difficult to apply due to lack of information in the dataset. This would require, for a section, to have the entrance and exit timestamps of each GPS receiver, or at least the exact timestamp of each GPS record (and not just the section timestamp), which would then allow to assume a time-spent per vehicle based on the length of the section and the speed.

The common time frame Δt used is 3 mn long. The section Δx is the entire ringway mainline, inner and outer roadways combined. The comparison is carried out for June 2014 data, business days.

Note that physically, loops cannot measure zero speeds, as they fundamentally measure a time elapsed between two rising edges of an electrical signal triggered by the *movement* of a vehicle over them. A zero speed would mean an infinite time between the two rising edges. Moreover, $V_i(t)$ are, as stated before, harmonic means of speeds, which therefore cannot be computed with zero values. Therefore, $V_{LOOPS} = 0$ logs are the result of the algorithm behind the loops data. The Author will also compare the average of the running mode $\overline{V_{GPS,r}}$ with the average of loops speed for $V_i(t) \geqslant 5$ km.h^{-1}.

The compared distribution of the loops average speed $\overline{V_{loops}}$, the GPS average speed $\overline{V_{GPS}}$, and the GPS running mode average speed $\overline{V_{GPS,r}}$ is plotted on Figure 7.14, along with a kernel density estimate of each distribution. The bimodality of the distribution is reflected by all three variables; a closer analysis can even show a trimodality: a "slow" mode, which can be split into two modes, and a "fast" or "free-flowing one", nearer the speed-limit.

There are several main reasons standing behind the bi- or trimodality:

- the first is the time-dependence of the variables, as shown by the time series of the three variables, plotted on Figure 7.15. The average evolves in three well-bounded sequences: night free-flow (22:00 to 06:00), peak hours (07:00 to 10:00 and 15:00 to 21:00), mid-day (10:00 to 15:00), plus the transitional phases.
- the second is the spatial-dependence of the variables: the averages are computed over the whole ringway, sections of which are more or less congested during the day.

Both the distribution and the time-series show that loops-based and GPS-based averages evolve in the same range of values, roughly distributed the same way, and follow the same time variations. The already pointed importance of the zero-speeds recorded by GPS receivers is highlighted, as the running-mode average speed $\overline{V_{GPS,r}}$ is between 5 and 10 km.h^{-1} above the all-mode average $\overline{V_{GPS}}$. The Author was surprised by the close agreement between the loops-average $\overline{V_{LOOPS}}$ and the all-mode average $\overline{V_{GPS}}$, both in terms of distribution and time variation, the gap being contained between 0 and 5 km.h^{-1}, the distribution being shown by Figure 7.16.

The analysis of speed distributions from two sources, namely the legacy double-loops and the newcomed GPS speed, allows a deeper analysis of the consequences of a speed-limit change, while not requiring the deployment of additional infrastructure. The analysis shows that the speed-limit change had macroscopically no consequence on the levels of traffic sustained by the ringway.

As the reciprocal of travel-time, speed allows both to catch the service delivered to the user and to the traffic flow in general. In terms of traffic flow, the loops speed is pertinent and accounts for it, as it is itself a time-average made at specific locations, and estimates the flow speed (or

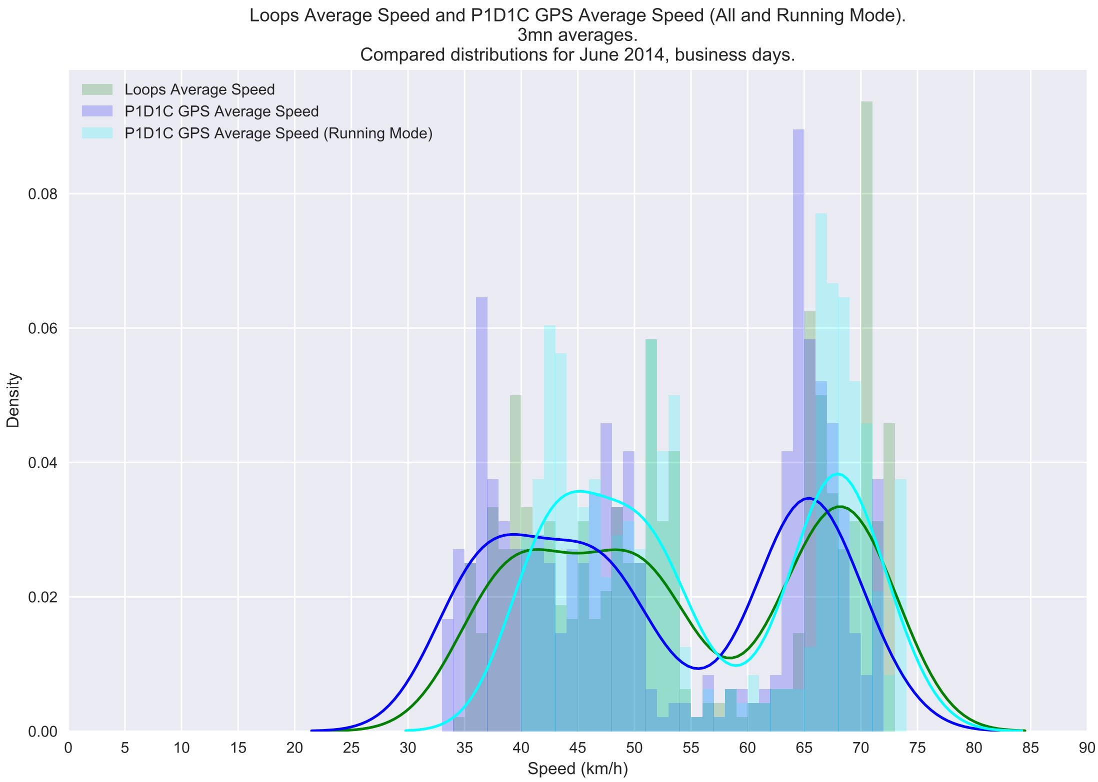

Figure 7.14 – Provider 1. First delivery. Compared Average Speeds for P1D1C dataset (All $\overline{V_{GPS}}$ and Running Mode $\overline{V_{GPS,r}}$) and Loops V_{LOOPS}. Business days of June 2014.

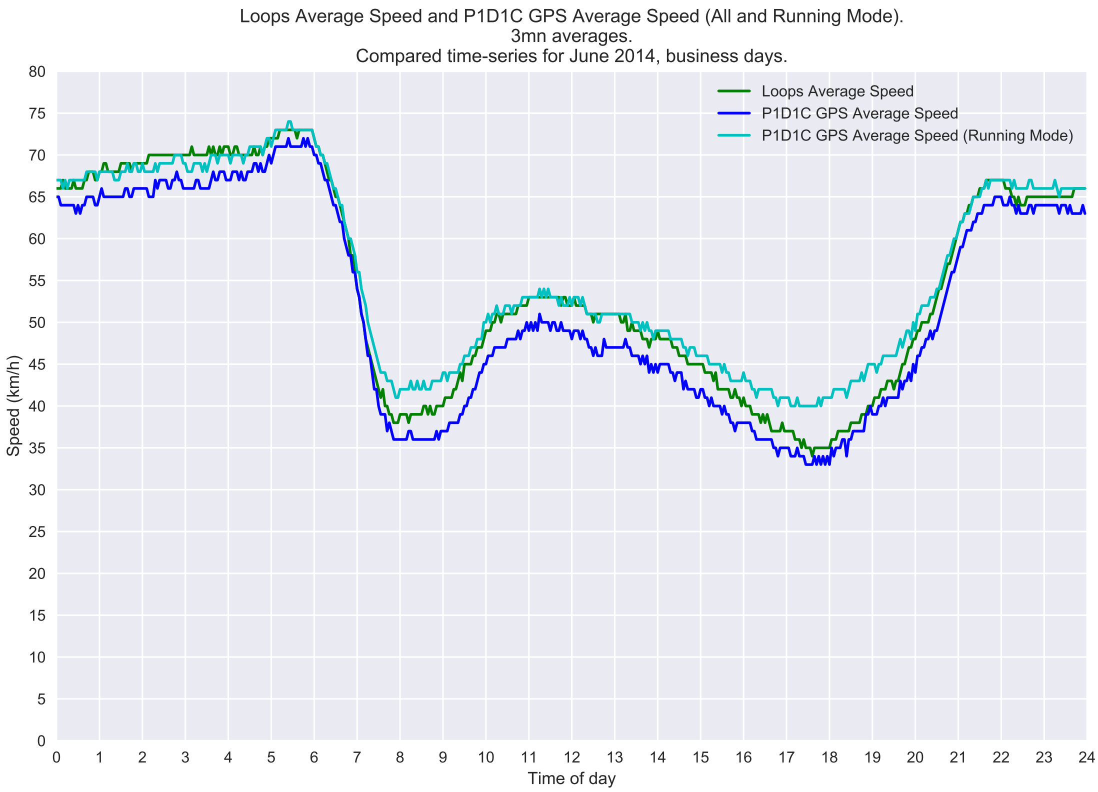

Figure 7.15 – Provider 1. First delivery. Compared Average Speeds for P1D1C dataset (All and Running Mode) and Loops. Business days of June 2014.

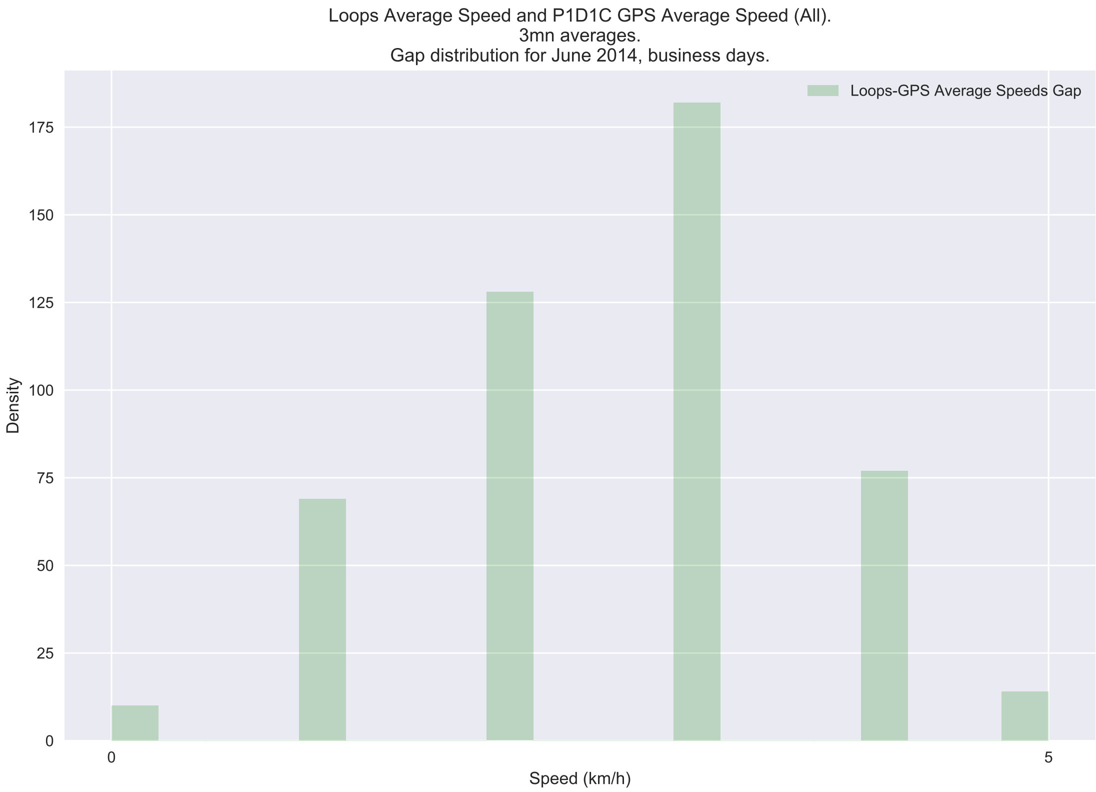

Figure 7.16 – Provider 1. First delivery. Distribution of gaps between average speeds for P1D1C dataset (All Modes) and Loops. Business days of June 2014.

space-mean speed). Averaging arithmetically GPS speeds is another way of estimating the flow speed. The compared analysis shows that the speed-limit change had no perceptible-effect on the traffic flow speed, or average journey speed, except on the free-flowing conditions.

The analysis of the distribution of GPS instantaneous speed accounts for individual measurements, and quantifies the variability both through time and space of the speeds, which the loop speeds only catches very partially. The analysis of its distribution shows that the speed-limit had an effect on the variability of speeds, by reducing the range of values, both in free-flow conditions, but also in mid-day. No consequences can however be seen for peak periods.

While the Author was drawing its conclusions for the City of Paris, an outside assessment was carried out by a private company, INRIX, and published with great publicity [144]. In its press release, widely taken up by both local and national French medias, INRIX claimed that "congestion has been slashed by 36 % on average from 2013, when the speed-limit was 80 km.h^{-1}" ([144]), stating that "freeing up traffic [was an] unexpected result" ([144]). The limit between free-flow and congestion was arbitrarily set to 40 km.h^{-1}, and the study compared daily average time spent under this limit between the first half of 2013 and the first half of 2014. The number of minutes per day during which the average speed was under 40 km.h^{-1} was computed.

Beyond the traffic-related critics that this study could face (figures in the previous sections show a different view), the INRIX report shows another aspect of traffic conditions assessment by the "new" traffic data: the fact that the traffic authority in charge does not control all the data produced by the traffic on its network anymore, nor does it control what is done with it. "Outsiders" can also carry out traffic studies and challenge the authority's role in the assessment of the policies it implements or oversees. This type of study is a real blow to the exclusivity traffic authorities used to have on traffic-related matters. They are not only challenged by individuals based on "personal experience": other outside the authorities can now also access lots of "personal opinions" and data, "big data", and draw their own conclusions and serve their own purposes.

7.5 Conclusion

Speed-limit reduction policies serve two main purposes: safety and the environment. Beyond the research aspects, these two fields are highly sensitive political topics. Strong empirical evidence has allowed to build models linking the driving speed with the crash fatality risk or the pedestrian fatality risk. The environmental aspects are also thoroughly investigated: energy consumption, noise and air pollution. Nonetheless, the expected improvements, especially for noise and air pollution, of lowering the speed are still not clearly shown and still debated.

GPS speed datasets are well suited for the assessment of speed-related policies.

The first assessment was the extension of 30 km.h^{-1} zones on local streets, without the usual roadway layout modifications meant to force motorists to slow down, like speed bumps.

On local streets, the availability of GPS speed data for off-line analysis remains satisfactory, with the help of two aspects: using both the space (a zone of several streets) and time (a month period) depth of coverage offered by off-line datasets. The computation of a linear density of data is a helpful tool to assess the effective coverage.

The comparison of the GPS instantaneous speed distribution before and after the speed-limit change shows the measure had little to no effect on the speed of vehicles. In fact, the speed distribution was already mostly below the 30 km.h^{-1} speed-limit before it was officially lowered, both when considering all modes or simply the running mode. This, in a way, shows that for the most part, drivers adapt their speed to the local setting. Moreover, it may be hinted that a behavior change with these low speeds is not triggered by a speed-limit change, as the last quartile of speed records is still above 30 km.h^{-1} after the speed-limit change.

The second assessment of a speed-limit change was about on of France's busiest roads, the Paris ringway, whose speed-limit was lowered from 80 to 70 km.h^{-1}.

The analysis of speed distributions from two sources, namely the legacy double-loops and the newcomed GPS speed, allows a deeper analysis of the consequences of a speed-limit change, while not requiring the deployment of additional infrastructure. The analysis shows that the speed-limit change had macroscopically no consequence on the levels of traffic sustained by the ringway.

As the reciprocal of travel-time, speed allows both to catch the service delivered to the user and to the traffic flow in general. In terms of traffic flow, the loops speed is pertinent and accounts for it, as it is itself a time-average made at specific locations, and estimates the flow speed (or space-mean speed). Averaging arithmetically GPS speeds is another way of estimating the flow speed. The compared analysis shows that the speed-limit change had no perceptible-effect on the traffic flow speed, or average journey speed, except on the free-flowing conditions.

The analysis of the distribution of GPS instantaneous speed accounts for individual measurements, and quantifies the variability both through time and space of the speeds, which the loop speeds only catches very partially. The analysis of its distribution shows that the speed-limit had an effect on the variability of speeds, by reducing the range of values, both in free-flow conditions, but also in mid-day. No consequences can however be seen for peak periods.

The ringway speed-limit change is also an example of the consequences of the change in traffic data production. "Outside" assessments of politically-sensitive measures such as lowering the speed on an expressway can be carried out. While the Author was drawing its conclusions for the City of Paris, an outside assessment was carried out by a private company, INRIX, and published with great publicity [144], claiming a huge decrease of the congestion thanks to the speed change. Politicians therefore felt their decision backed by the facts, despite the limitations of INRIX's study and the "in-house" report showing that the speed change had little to no consequences on flows and traffic conditions.

The traffic authority in charge does not control all the data produced by the traffic on its network anymore, nor does it control what is done with it. "Outsiders" can also carry out traffic studies and challenge the authority's role in the assessment of the policies it implements or oversees. This type of study is a real blow to the exclusivity traffic authorities used to have on traffic-related matters. They are not only challenged by individuals based on "personal experience": other outside the authorities can now also access lots of "personal opinions" and data, "big data", and draw their own conclusions and serve their own purposes.

Conclusion of the Second Part

Part II addressed the two following issues:

1. What data can the Traffic Management Center "catch" outside of its legacy sensors infrastructure?
2. What are the operational traffic indicators these "new" traffic data provide? What operational purposes can they serve for the Traffic Management Center?

Outside of its legacy sensors infrastructure, the Traffic Management Center can "catch", through private intermediaries, more-or-less aggregated data coming from the devices traveling onboard the vehicles or with the users.

The experiments carried out in Paris made use of the two most widely used of these "new" data: Bluetooth data and GPS FCD speed data. In both cases, the data was used for traffic studies, assessing traffic-impacting political decisions. No real-time application was carried out.

The Bluetooth data yields travel-time, and the GPS FCD speed data yields speeds. Both the travel-time and speed (either instantaneous, time-mean or space-mean speed) are key indicators to assess traffic policies.

First, they "mean" something, whereas flow, occupancy requires some knowledge of the traffic in order not be misunderstood. Travel-time and its reciprocal, the space-mean or journey speed, are individual variables, each value being related to a specific, individual journey.

Second, the combination of these individual journeys make up distributions, time series that can be analyzed by the Traffic Management Center. The distribution means that not only the central tendency can be used, like it was historically measured, but also the dispersion of the values, which is a direct observation of the variability of each of the variables. Before these data were available, the dispersion of journey-related values could only be observed at great cost, through manned observations or complex roadside systems (the loops could give a per-vehicle observation, but only at their location, not for a journey).

Chapters 4 and 5 showed that the use of Bluetooth technology allowed the collection of individual, equipment-related travel-times to assess traffic-impeding measures traffic loops data would have hardly allowed to assess. They also illustrated the complexity of installing such devices in a constrained urban environment, with many parties at stake.

The collected travel-times were at first experimented on Place de l'Etoile, one of the main intersections of the Paris arterial network. They allowed to measure, from user-perspective, the travel-times before and after the closure of the tunnel grade-separating the intersection for one of its major turning movement. Users could even be distinguished between two main categories that make up the traffic: motorized two-wheelers and cars.

After the Etoile's tunnel closure, the new massive traffic-impeding policy of the City of Paris involved the closure of the main expressway crossing the city center. Bluetooth travel-times became key journey-related indicators to follow the arterials on which traffic mostly deviate, from the city's boundaries to the cross-city center arterials.

Bluetooth travel-times offer an user-perspective to the Traffic Management Center: the travel-times distributions are drawn from individual equipment's travel-times, and not from averages such as the traffic loops data. These distributions yield two key informations: central tendency, such as the median or mean travel-times, traditionally used to summarize situations, but also the spread of the values around these tendencies. Quantifying the spread is a direct measurement of the variability of the travel-time, i.e. of the reliability of the route for the user. As a direct consequence, if the average travel-time was to broadcasted to the user, distributions of individual travel-times such as the one yielded by the Bluetooth beacons gives the user the probability he has to encounter such travel-time.

The direct comparison of travel-times distributions yielded the awaited operational conclusions regarding the traffic-impact of the expressway's closure: highly increasing travel-times, and a decreasing reliability of the diversion routes, as the spread of travel-times values increased.

Bluetooth travel-times also allow, given a careful analysis, to discriminate competing routes over the same origin-destination.

Results obtained from the Place de l'Etoile study were also confirmed, regarding the split of the equipments population into two major groups, namely the Headset group, accounting for motorized two-wheelers, and the Phone group, accounting for more general traffic. Of course, other users categories, such as public transit (passengers of buses) were not considered in the Author's approach. He believes the subject is more in the hands of the companies providing the Bluetooth beacons, who have access to additional information such as the signal's intensity of each Bluetooth-enabled equipment within the detection range. The instantaneous detection of multiple devices could hint the passage of a bus near a beacon. Nonetheless, this option was ruled out for the Berges experiment, as the beacons were quite far apart and it was believed the number of equipments actually traveling the few bus lines that traveled the studied origin-destinations would be very limited.

Observed travel-times trends throughout several months periods seem more to speak of the seasonal variations of traffic than a possible change of routing strategies by the users. Despite the worsened traffic conditions, there is still a demand that makes use of all available capacity on diversion routes.

In the end, three factors influence the shape of the Bluetooth travel-time distribution over an origin-destination:

- the traffic demand, whose direct consequence is the strong time dependency of the travel-times;
- route choices: if there are several competing routes for a same origin-destination, this will be found in the global travel-times distribution;
- the population of equipments: different categories have different uses of the roads, and hence different travel-times.

Unlike the Bluetooth, which are fixed road-side traffic sensors, the GPS-based FCD data entirely relies on vehicle and user devices, and therefore the TMC has no direct control on its production. It has to rely on an intermediary: a private GPS FCD data provider.

Chapters 6 and 7 show the complete TMC-circuit of archived GPS data, from tendering, to confronting the datasets, identifying their shortfalls, and at last use them for operational studies, one of the most suitable for speed data being the speed-limit changes.

Chapter 6 illustrates the issues encountered with the necessary outsourcing of GPS data acquisition. It also offers a chance to provide operational guidelines to deal with the issues, and in the end clear out most of them.

GPS terminals are the first technology allowing widespread collection of the traffic state in the

100 years of traffic engineering. It samples through both time and space the speed of equipped vehicles. Traffic Management Centers face this breakthrough, mostly developed in private hands, with at first sight a very reduced array of tools. Nevertheless, this chapter shows that through the main instrument of interaction between the public and private worlds - tenders -, with the help of some simple descriptive statistics (distributions, time series, aggregate statistics, ranking), many of the advantages and shortfalls of the GPS FCD data can be highlighted. Not being behind the technical system collecting the data, like the TMCs were for the traffic sensors, doesn't mean they cannot acquire a deeper knowledge of it, be able to identify its flaws and exchange with the providers.

The shortfalls and "strange behaviors" discussed here show how algorithm and filtering decisions can radically transform the final rendering of the dataset, far from the original data, and more or less hidden when solely considering means or medians. Filtering must always be done consciously and the side effects of any of such process must be, as much as one can hope for, clearly analyzed.

The datasets of this chapter also introduce some of the fundamental questioning at stake in traffic engineering, to which only partial answers and assumptions could be given due to the lack of financially viable widespread observation techniques. Among the questions raised, it glanced at the definition of the areas of observation through time and space, and how it influences the resulting variables (speed, in the present case). Another aspect is the profound variability of the observed data, and the fact that GPS FCD allows to quantify it.

Chapter 7 shows a key operational use of GPS FCD speeds: assessing speed limit changes.

Speed-limit reduction policies serve two main purposes: safety and the environment. Beyond the research aspects, these two fields are highly sensitive political topics. Strong empirical evidence has allowed to build models linking the driving speed with the crash fatality risk or the pedestrian fatality risk. The environmental aspects are also thoroughly investigated: energy consumption, noise and air pollution. Nonetheless, the expected improvements, especially for noise and air pollution, of lowering the speed are still not clearly shown and still debated.

GPS speed datasets are well suited for the assessment of speed-related policies.

The first assessment was the extension of 30 $km.h^{-1}$ zones on local streets, without the usual roadway layout modifications meant to force motorists to slow down, like speed bumps.

On local streets, the availability of GPS speed data for off-line analysis remains satisfactory, with the help of two aspects: using both the space (a zone of several streets) and time (a month period) depth of coverage offered by off-line datasets. The computation of a linear density of data is a helpful tool to assess the effective coverage.

The comparison of the GPS instantaneous speed distribution before and after the speed-limit change shows the measure had little to no effect on the speed of vehicles. In fact, the speed distribution was already mostly below the 30 $km.h^{-1}$ speed-limit before it was officially lowered, both when considering all modes or simply the running mode. This, in a way, shows that for the most part, drivers adapt their speed to the local setting. Moreover, it may be hinted that a behavior change with these low speeds is not triggered by a speed-limit change, as the last quartile of speed records is still above 30 $km.h^{-1}$ after the speed-limit change.

The second assessment of a speed-limit change was made on one of France's busiest roads, the Paris ringway, whose speed-limit was lowered from 80 to 70 $km.h^{-1}$.

The analysis of speed distributions from two sources, namely the legacy double-loops and the newcomed GPS speed, allows a deeper analysis of the consequences of a speed-limit change, while not requiring the deployment of additional infrastructure. The analysis shows that the speed-limit change had macroscopically no consequence on the levels of traffic sustained by the ringway.

As the reciprocal of travel-time, speed allows both to catch the service delivered to the user and to the traffic flow in general. In terms of traffic flow, the loops speed is pertinent and accounts for it, as it is itself a time-average made at specific locations, and estimates the flow speed (or space-mean speed). Averaging arithmetically GPS speeds is another way of estimating the flow speed. The compared analysis shows that the speed-limit change had no perceptible-effect on the traffic flow speed, or average journey speed, except in free-flowing conditions.

The analysis of the distribution of GPS instantaneous speed accounts for individual measurements, and quantifies the variability both through time and space of the speeds, which the loop speeds only catches very partially. The analysis of its distribution shows that the speed-limit had an effect on the variability of speeds, by reducing the range of values, both in free-flow conditions, but also in mid-day. No consequences can however be seen for peak periods.

The ringway speed-limit change is also an example of the consequences of the change in traffic data production. "Outside" assessments of politically-sensitive measures such as lowering the speed on an expressway can be carried out. While the Author was drawing its conclusions for the City of Paris, an outside assessment was carried out by a private company, INRIX, and published with great publicity, claiming a huge decrease of the congestion thanks to the speed change. Politicians therefore felt their decision backed by the facts, despite the limitations of INRIX's study and the "in-house" report showing that the speed change had little to no consequences on flows and traffic conditions.

The traffic authority in charge does not control all the data produced by the traffic on its network anymore, nor does it control what is done with it. "Outsiders" can also carry out traffic studies and challenge the authority's role in the assessment of the policies it implements or oversees. This type of study is a real blow to the exclusivity traffic authorities used to have on traffic-related matters. They are not only challenged by individuals based on "personal experience": others outside the authorities can now also access lots of "personal opinions" and data, "big data", and draw their own conclusions and serve their own purposes.

Road authorities can now easily have access to journey-related variables, and therefore adopt a user-perspective when assessing traffic policies.

This also induces a change in the way their network management strategies are designed: loops deliver averaged information about the traffic flow, and schematically, the purpose of a TMC would be to maximize the flow on each road, either an arterial or an expressway. The question of the quality of the service provided, in terms of individual time of travel and not only flow, must be taken into account. Private companies, routing their individual users from crowdsourced data, being the primary collectors of the data their user-base generates, have already taken this step.

General conclusion

1 The political context: reducing motor traffic in Paris

The increasing scrutiny on motor traffic externalities (air quality, noise, used space...), especially in dense and congested urban areas like the City of Paris, has triggered major political decisions aimed at reducing motor traffic. The Parisian traffic-related policy relies on two main levers: parking and infrastructure (acting on the supply) on one hand, and vehicle fleet control through a low emission zone (acting on the demand) on the other. A congestion charge, implemented in many cities across Europe, has been deemed politically unacceptable.

Major decisions regarding the infrastructure were made by the current City of Paris Administration in the 2014-2016 period through:

the closure of two key infrastructures, namely the tunnel under Place de l'Etoile, one of Paris major intersections, and the central section of the "Voie Express Rive Droite", an expressway which provided 37,000 vehicles per day a nearly lights-free journey from West to East, across the city center)

the reduction of speed limits, with the speed limit dropped from 80 to 70 km.h^{-1} on the ringway and the extension of 30 km.h^{-1} zones.

These were the case studies in which the author was directly involved, and on which he based his thesis work.

2 The operational context: the Poste Central d'Exploitation Lutèce, monitoring traffic on Paris arterials

2.1 The missions of the PCE Lutèce

The City of Paris is the sole authority in charge of the road network within its boundaries, although some prerogatives are shared with the French State police. The "Direction de la Voirie et des Déplacements" (DVD) is the City's Administration department embodying the City's traffic authority role. Within the DVD, the "Poste Central d'Exploitation Lutèce" (PCE Lutèce) is the Traffic Management Center (TMC) overseeing Paris signalized arterials.

The PCE Lutèce's primary mission is to operate traffic assets over Paris main arterials, ensuring the safety of the road network's users. This is done by providing near-permanent availability of the safety-related equipments, namely the traffic lights.

Beyond the safety-related aspects, the PCE Lutèce implements traffic management policies over the signalized arterials (coordinated signal actuation, transit signal preemption, traffic information, etc.).

The PCE Lutèce is also responsible for the traffic studies of traffic-impeding measures, like the ones mentionned above.

2.2 A centralized and comprehensive technical infrastructure to support its missions

To carry out its missions, a Traffic Management Center like the PCE Lutèce needs to remotely know the state of the road network and related ground assets. It relies on a centralized computer system (SURF3) wired to the signalized intersections and in-road traffic sensors (mainly inductive loops). This architecture allows the Traffic Management Center to remotely operate the lights (failure alarms, signals timing, green waves, transit line priority...) and collect traffic data measured by the sensors infrastructure (loops).

The information collected and centralized by the system, which is under complete control of the Traffic Management Center's structure, is meant for two main parties. The first party is the Traffic Management Center itself, in both its traffic assets monitoring (real-time application) and traffic studies (archived data application) roles. The second party is informing the road users on the state of traffic and events (construction, incidents) impeding it.

2.3 Traffic indicators: quantifying the traffic and assessing congestion

Traffic indicators derived from the centralized Traffic Management Center's infrastructure hold three main operational roles:

the political reporting on the traffic state, from routine reporting to specific project before-after studies;

the real-time network operation (traffic management);

the in-house traffic studies, feeding both the political and technical decision-making processes.

The projects impeding traffic such as the ones studied by the author often trigger a fundamental issue: assess the decrease of motor traffic over Paris arterials, the rate of which being very politicized.

Three indicators are computed by the PCE Lutèce out of its system and sensors, over the arterials it monitors:

average hourly flow rate (in veh.h^{-1}), also referred to as normalized vehicle kilometers traveled (VKT_{norm}), which summarizes the flow rate measured by the system's traffic count stations;

the average speed (in km.h^{-1}), also referred to as the BRP speed, V_{BRP}[2];

the average availability of the traffic sensors (in %).

The decrease of traffic volume over Paris main arterials network for the 2001-2018 period nears 40 %, as measured by the centralized Traffic Management Center's sensors infrastructure. While this decrease is politically satisfying, the period also shows the decrease of two other key indicators: the network average speed drops by over 15 %, and the average availability of sensors by over 15 %.

In fact, important traffic-impeding measures like those that the author dealt with, on heavily traveled arterial networks like Paris', inevitably leads to congestion: when the supply (the infrastructure) is lower than the demand (the vehicles), meaning the vehicles cannot travel at their desired speed. In the case of the aforementioned measure, the supply is on-purpose reduced to allow less vehicles through.

[2] The algorithm's name has nothing to do with Bureau of Public Roads (BPR) formulas, despite the rather confusing and unfortunate naming proximity. BRP refers to the initials of its inventors, Bonvalet and Robin-Prévallée [77].

Two indicators are needed to estimate congestion [145]: its extent (the number of vehicles or users impeded) and its severity (the maximum delay imposed). The extent and severity can be naturally linked to the indicators produced by the Traffic Management Center's infrastructure: the extent of congestion can be estimated through the flow (or traffic volume), and its severity by speed (or its reciprocal, the travel-time).

The author thus raises the following preliminary question: isn't the decrease of the traffic volume not only explained by the closure of infrastructures, but also by both the rise of congestion (the decrease in number of actual vehicles on the road is smaller than the decrease in flow) and the demise of the fixed sensors infrastructure? Regarding congestion, how can it be properly measured if the legacy sensors infrastructure breaks?

2.4 A major technological shift in traffic data collection: "new" traffic data

While the City of Paris traffic indicators rely on the centralized Traffic Management Center's infrastructure, a major and still ongoing technological shift has occurred in the late 2000s-2010s, leading to so-called "new" traffic data: the general availability of individual travel-times and speeds measurement technologies, based on crowdsourcing. This relies on probe vehicle technology: units onboard vehicles (GPS terminals, car computers, ...), or carried by their passengers (smartphones) massively probe journeys, transmitting timestamped positions or speeds.

The nature of these onboard units gives the private sector considerable weight and breaks the near-monopoly the Traffic Management Center previously held on traffic data and information. This questions how the road authority, and the Traffic Management Center in particular, can access and control privately generated traffic data, like it does with the data produced by its own infrastructure. This question is internationally grasped, like shown by both the rise of international private companies providing traffic information and the legislative production on the subject, embodied by the 2010 "ITS Directive" of the European Parliament and Council of the European Union [126].

These "new" data also trigger deep changes in the organization of the Traffic Management Center and the way it manages its network. Even when they were still considered as "emerging", the massive collection of individual travel-times or speeds "can result in better and more responsive dynamic traffic management applications with a richer background" ([146, p. 146]).

3 The author's research question

The author, a working engineer at the PCE Lutèce throughout his thesis, states his research question in this political and operational context.

The political context is drawn by the multiplication of traffic-impeding policies which dramatically affect the road network.

The operational context is the crossroad at which a legacy Traffic Management Center like the PCE Lutèce stands:

- its key role in ensuring the safety of users journeying on the network they manage;
- aging centralized system whose maintenance and development costs have become hardly sustainable;
- the need for traffic indicators (for political reporting, for traffic management, for traffic information) historically based on the centralized system traffic data;

- the questions raised by the technological shift created by massifying individual travel-times measurements (traffic data nature, private providers acting as traffic data producers independently of the Traffic Management Center's perimeter).

The author states his research question: **from the perspective of a road authority, what are the metrological and organizational changes induced by the technological shift triggered by the new methods of travel-time measurement?**

4 The author's response to his research question

The author organized his response to his research question into two parts.

In Part I of his dissertation, entitled Traffic data and traffic information: linking the Traffic Management Center and the driver, the author investigates the technical filiation of current centralized traffic management systems, in an effort to understand how the means available to observe traffic shaped traffic engineering and lead to the current "legacy" traffic indicators. Understanding this filiation allows to grasp the technological shift induced by the rise of individual travel-time measurement technologies, for the traffic indicators used to assess congestion (volume, travel-time, speed) in general, and for the Paris Traffic Management Center case in particular.

In Part II of his dissertation, entitled "New" traffic data: expanded ways to assess traffic, the author relates the applications he carried out of some of the individual travel-time measurement techniques on Paris arterial network. He worked with two data collection technologies, namely Bluetooth sensors and GPS speeds. While in the end showing the faisability of the solutions and their operational usefulness, he also illustrates the issues he encountered in their impementation and proposes the solutions he used to overcome them.

4.1 The technical filiation of centralized traffic management: the legacy of the point observation of traffic

To understand the technical filiation of centralized traffic management, the author based his work on two approaches. The first approach was to analyze a personal selection of "landmark" traffic engineering papers and reports from an operational perspective, namely the 1910s-1960s works of Johnson et al. (1910s-1930s), Greenshields (1930s-1950s), Lighthill and Whitham (1950s), Wardrop (1950s), and Edie (1950s-1960s). The second approach, more centered on Paris, was the thorough analysis of archive material documenting the construction of the traffic management infrastructure of the City of Paris, from the first traffic light coordination systems in the 1940s to the current PCE Lutèce.

Both traffic volume (and its associated indicators: flow, vehicle kilometers traveled) and travel-time were from the start identified as key indicators to monitor the state of the road network. The issue during the great road-building era during which these engineers worked was both to fund the modernization of the network but also the profitability of the investments: does the road allow more vehicle through? Is there less delay?

The traffic volume and travel-time were already understood both in their time and space dimensions, and that therefore they were to be measured not only through time at a given point, but across the network. With the technology available at the time, spatial measurement required huge investments. Johnson was one of the few who undertook comprehensive campaigns to measure traffic as it is (a spatio-temporal phenomenon), but it required flying an airplane, having dedicated cars "floating" with the traffic and roadside ground observations, all backed by considerable manpower to make the measurements and process the collected data.

Catching the spatial dimension of traffic was always in the mind of traffic engineers, but could only be approximated through the most viable technical option: automatic point observation at ground level. The traffic theory and traffic management systems stemmed from point observations: the work was initiated by GREENSHIELDS and pursued by WARDROP, who formalized the traffic variables definitions based on how they were collected [28], and LIGHTHILL and WHITHAM and RICHARDS who designed a model, known as LWR, for traffic flow out of point observations, based on an analogy with fluid mechanics. In the end, the author considers this story to be one of a compromise between technology and operational needs.

The "legacy" traffic data therefore designates data stemming from point observation systems, like inductive loops. An inductive loop is a solenoid inserted a few centimeters beneath the road surface (the solenoid's shape is a 1 m by 1 m square in Paris). By design, the loop only measures traffic during a period of length Δt over a small length dx: in a time-space, or t–x, diagram, the observation frame of the loop will be a $\Delta x \times \mathrm{d}x$ rectangle, as shown by Figure 17. The elementary measure it provides over Δt is the time-occupation, described in t–x as the intersecting area between the trajectory of vehicles (in grey on Figure 17) and the observation frame (in red). The ratio of both areas is known as the occupancy, and is a widely used traffic variable to qualify the traffic state, from free-flow to congested.

The second measure the loop provides is the flow, by counting the number of "trues" if considering that no vehicle over the loop returns a "false" state.

The third measure the loop provides is the local speed, by timing the passage of each vehicle over the loop (or over a dual-loop: the loop is then duplicated by another one at a given distance). The average of such speeds yields the time-mean speed. The average travel-time of the vehicles across the loop, inversed by the loop's length, yields the space-mean speed at the location of the loop.

Through the Figure 17 diagram, the author shows the limits of the loop measuring technique: the values produced heavily depend on its position. This is even more critical on signalized arterials, where there is great space heterogeneity of traffic, not only induced by congestion, but also by the intersections (traffic lights). The data produced by the loops is essential local and not spatial. The aforementioned average speed indicatorxs, or BRP speed, is therefore derived from two assumptions: what the loop measures properly estimates the average traffic conditions of the road section it is associated with, and the road section's average travel-time is a linear function of occupancy. Given what was previously mentioned, this has gradually become a questionable method, which the author's work backs.

4.2 Experimenting and assessing "new" traffic data: a critical analysis of the work carried out

In this section, the author aims at confronting his experimental work, presented in Part II, to the conclusions drawn by the CEREMA these last few years. The CEREMA, "Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement" [147], is a key public body dedicated to provide engineering and expertise support to both local and national authorities, focusing on land-use planning, transport, energy, environmental and urban issues. Among other missions, its "Transport and Mobilities" department provides support and expertise in traffic management and traffic information [148].

Due to the nature of the State-managed network, which mostly consists of inter-urban or urban expressways, many of the CEREMA studies the author read to offer this critical stand of his work were carried out on expressways and not on signalized arterials. This is also explained

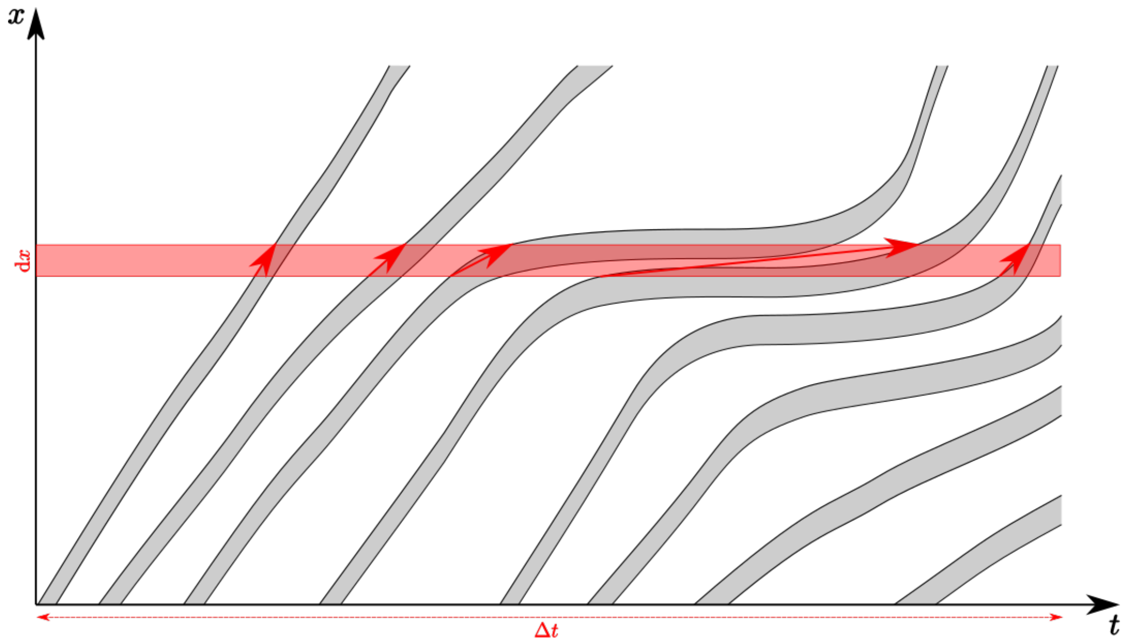

Figure 17 – Time-space t–x diagram showing traffic viewed by a fixed point sensor during a period of length Δt *over a small length* $\mathrm{d}x$.

by the fact that expressways concentrate the highest traffic levels and congestion issues, and constitute the critical element of the urban road networks.

The major CEREMA study on travel-times, carried out in 2014-2015 on the N346 expressway which bypasses Lyon [149], compared several travel-time measurement techniques, among which the legacy loops-based algorithm, Bluetooth and GPS travel-times.

The latter, among with other studies the author analyzed [150], yielded two major documents meant to serve as guidelines to future use of Bluetooth and GPS technologies: a report on the interest of real-time FCD data for road authorities [151], and another one on travel-time metrology [152].

4.2.1 The difference of nature between GPS and Bluetooth travel-times

The author carried out several experiments of new travel-time measurement systems, which are described in Part II. He made use of two measurement systems:

Bluetooth travel-times, obtained from roadside Bluetooth beacons, are point-to-point travel-times. A Bluetooth-enabled equipment is sniffed by two successive beacons during his journey: each beacon timestamps its unique Media Access Control (MAC) address. The difference in timestamps provides a travel-time for the detected equipment. The use of Bluetooth technology for travel-times was first hinted in the mid-2000s [153]. Figure 18 shows how detection of vehicles traveling with Bluetooth-enabled equipments onboard compares with legacy loop detection.

Floating Car Data GPS speeds, obtained from GNSS location: the trajectories of equipped vehicles are sampled, generally at a fixed time rate, as Figure 19 shows (trajectories in green, dots represent the GPS position). To each GPS position, two speeds can be associated: an instantaneous speed, computed by the GPS receiver at the time of the signal's emission, and a positional speed, or average speed between two positions, computed as the ratio of the distance traveled on the network by the time elapsed between the two positions.

In his work, the author did not necessarily make a clear distinction between the average travel-time he derived from Bluetooth measurement than from the one he measured from GPS speeds.

Bluetooth travel-times are point-to-point travel-times: the same equipment is timestamped at two locations. It is very similar in nature to the legacy method of manually or automatically making timestamped readings of vehicles license plates at different location to derive their individual travel-times.

GPS speeds, and the travel-time that can be deduced from them, is somewhat different in nature: the "raw" GPS data sent by the GPS receivers must be map-matched to the road network. The GPS data the author worked with was aggregated to road sections, and average travel-time and speed was computed over these sections. This makes the definition of the sections very important, as both the author and the CEREMA [151] underline.

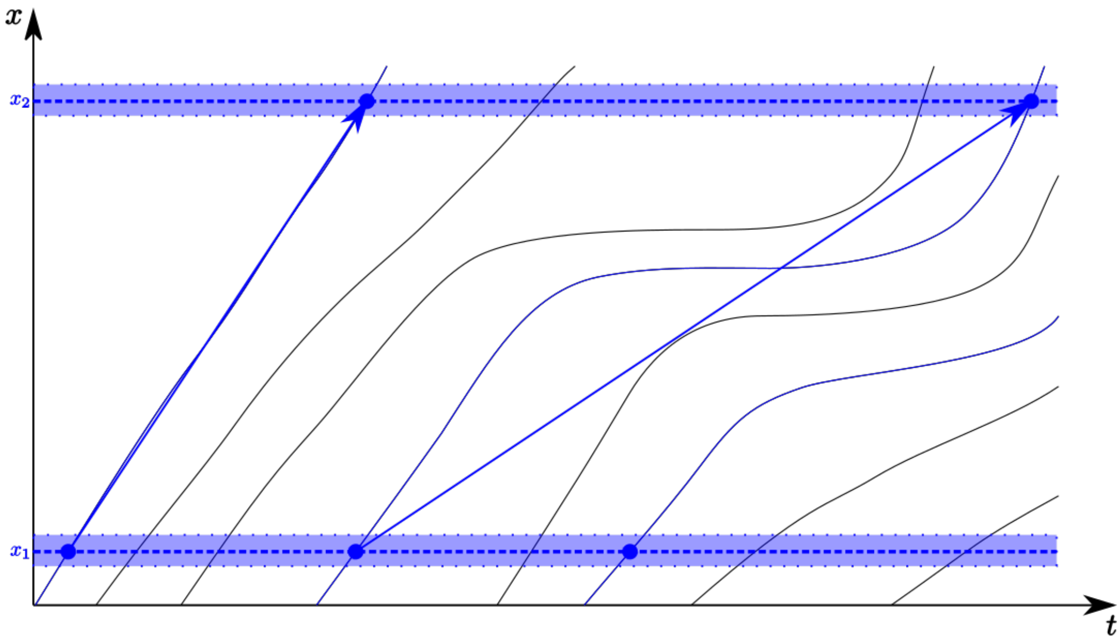

Figure 18 – Time-space t–x diagram showing traffic viewed by Bluetooth sensors through vehicle re-identification at locations x_1 and x_2. For each trajectory, the blue arrow represents the average speed between entrance and exit Bluetooth detections over the monitored section.

4.2.2 Assessing new travel-time measures, and the "reference" issue

The main issue for the author during the experiments was not only to assess the projects, but also the travel-time, or its reciprocal average speed, produced by the experimented systems. As recalled by Buisson [152] on travel-times (which is the essential indicator derived from "new" traffic data), there are two aspects to consider in assessing these "new" data:

- the metrological aspect, relative to the quality of the measurement made, against a reference;
- the user aspect, especially since there are two great categories of users: the Traffic Management Center, which basically seeks a real-time picture of the state of its network, and the user of the network, who seeks information before he starts his journey and while he journeys.

The author sought to make use of commercially available data (through tendering), therefore produced by closed-source proprietary algorithms. He focused on "off-line" rather than "real-time" applications.

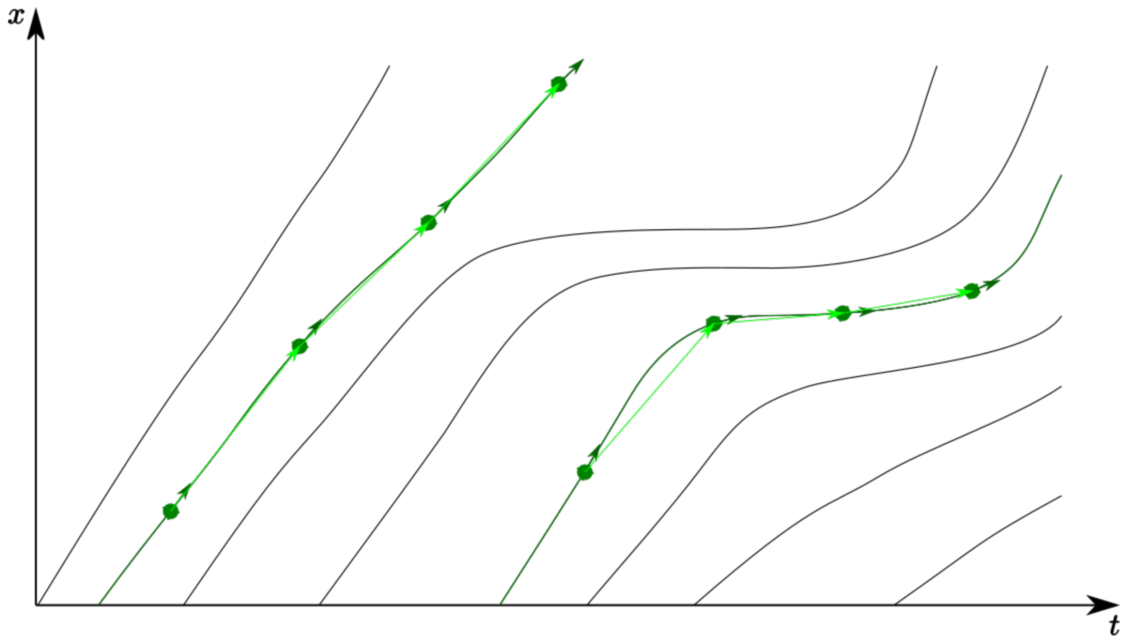

Figure 19 – Time-space t–x diagram showing traffic viewed by GPS-equipped vehicles, the dots representing the sampling of the equipped vehicles' trajectories at regular δt-long intervals. For each trajectory and position, the dark green arrow represents the instantaneous speed, whereas the light green arrow represents the positional speed, i.e. the average speed between two successive GPS positions.

The author situates his thesis work halfway between the two evaluation aspects. He investigated metrological aspects and raised several discrepancies, although his work lacked a proper reference to compare the values he collected. This reference should avoid bias, as the new methods only sample a part of the traffic, since to be probed the vehicles must carry the proper equipments. The penetration rate of such equipments varies in time, be it for Bluetooth or for GPS FCD data: their estimation of traffic is generally better in "heavier" than "lighter" traffic.

One of the currently most efficient system to collect a reference travel-time independent of fleet bias is the automatic number-plate recognition (ANPR) technology, which is like the Bluetooth travel-time, a point-to-point travel-time, relying on license plates of vehicles Buisson. The author lacked such reference travel-time to back his experimental results.

The author also investigated the usefulness of the data from the perspective of the Traffic Management Center as a user of traffic information, as the values he measured lead to indicators to be used in the assessment of the traffic-impeding projects he worked on (average travel-time or speed). He mostly left the network user perspective aside, although he found out that some of the data he worked on would not be directly suitable for user information. For instance, Bluetooth travel-times are only known once the vehicle has exited the monitored origin-destination: by the time it completes its journey, the traffic conditions may very well have worsened or improved. The user information resulting from pure Bluetooth travelt-time would therefore very likely be outdated if delivered to users about to enter the network.

4.2.3 Travel-time variability

In his experimental results, the author identified both the distributions of individual and mean values of travel-time or speed with the quantification of variability, through usual descriptive statistics (percentiles and variance).

By doing so, he confused two types of variability, as specified by Buisson [152]:

- the average variability: between two given periods of the same day (peak and off-peak for instance), or between two days, the general traffic conditions encountered by the vehicles measured may have changed, resulting in different averages.

- the individual variability: for the same period, during which the general traffic conditions remain stable, two individuals may have different travel-times. This is the distribution of individual journeys around the average journey. The differences can be caused by different factors: local congestion, missed green-wave (some users catch the green wave, while others drop it), factors which are to be encountered on a signalized arterial...

In his study, the author should have made a clear distinction between these two variabilities, which would have allowed him to better caracterize how the infrastructure projects influenced not only the general traffic conditions, but also individual journeys within.

5 Down the road... beyond the author's work

5.1 Possible real-time and off-line uses

The possible uses of the "new" travel-time collection technologies by a Traffic Management Center like the PCE Lutèce, namely here Bluetooth and GPS FCD, go beyond the scope of the author's study.

There are two temporal possibilities: real-time and off-line application.

In real-time, the Traffic Management Center needs to have an up-to-date overview of the traffic conditions on its network. This is classicly done by setting threshold values to travel-time or speeds on road sections, coloring them on a scale from green (free-flow) to congested (red). Bluetooth travel-times require roadside sensors, whereas GPS FCD does not require any ground equipment.

For real-time traffic monitoring, as already mentioned, Bluetooth travel-times may be complicated to be used alone, as a point-to-point travel-time is only measured when the vehicle completes its journey.

GPS FCD are very suitable for real-time applications, but as the CEREMA points out [151], there are still issues to circonvene, among which: only incidents resulting in a speed drop will be detected, the need of reasonable traffic in order to have enough GPS probes, the eventual latency of the GPS data feed, the integration of the data feed within existing centralized systems.

Offline application not only include before-after studies, but also origin-destinations (as carried out by the author) and accessibility (well represented by isochronous maps) studies.

5.2 Measuring congestion: the need for both "legacy" and "new" traffic data

Travel-time and speed are precious indicators to estimate the severity of congestion. Nonetheless, estimating its extent requires knowledge of the volume.

As of 2018, the varying penetration rates of both GPS and Bluetooth probes, depending on, among other factors, the level of traffic, the time of day, the speed of traffic, makes it impossible to derive a reliable traffic volume from probe volumes.

Therefore, there is still need for legacy traffic data, as the traffic volumes can still only be reliably collected from fixed traffic count stations.

5.3 Decaying point traffic sensors, outsourcing traffic data: challenges for Traffic Management Centers

The loss of control by the public sector is of concern: the Traffic Management Center's primary role is the safety of the users traveling on its network. How can the Traffic Management Center carry this fundamental mission and secure the required data feeds, while losing the technical and financial capacity to maintain its in-house fixed sensor infrastructure? For instance, traffic volumes is a critical data for many issues, like in the assessment of projects, and the author faced the delicate situation where traffic count stations were out of orders at key locations.

Several leads have been investigated in line with the rise of the "new" traffic data and the decrepancy of Traffic Management Center's sensor infrastructures, like reported in 2013 by Mathis for the French case, and which the author briefly mentions and comments as follows:

- a State-backed public information service, keeping in mind that the existing one was dismantled in 2016, three years after Mathis's report;
- a public-private system, in which the Traffic Management Center would base itself, at least partially, on privately produced traffic data: the author's work evolved in this context, pioneering, for the City of Paris, the use of individual travel-time sold by the private sector for traffic studies;
- a control of the public authorities over the broadcasted traffic information: the author's descriptive and statistical work on individual speed and travel-time records, getting, through tendering, as close as possible to the "raw" data (as produced by the probes), is in line with the strategy of having a public assessment of privately-generated traffic data;
- an integration of traffic information into a broader multi-modal information system: the author places his work upstream of this eventual integration, the rise of massive travel-time measurement yielding a quantity (travel-time) that can be compared across modes of transport.

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