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## The results of the CapTA model on the restrained RER A network

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### ABSTRACT

The CapTA model is developed to capture the capacity phenomena in passenger traffic assignment to a transit network. These pertain to the interaction of passenger traffic and vehicle traffic: vehicle seat capacity drives the internal comfort, vehicle total capacity determines internal comfort and also platform waiting, passenger flows at vehicle egress and access interplay with dwell time, dwell time drives track occupancy and in turn the period frequency of any service that passes the station along the line of operations, and then service frequency influences service capacity and platform waiting.

The RER A – the busiest commuter rail line in Paris– is provided as an application instance to serve as a showcase of the models capabilities and as a means to test its behavior. Some assignment results are showed for the line as a whole, but further analysis is focused on the busier westbound service, where 30 trains/hour can carry around 60,000 passengers/hour. The effect of a greater-than-scheduled dwell time on the service frequency is highlighted for the dense central trunk. The application instance sheds light to the characteristics of the passenger stock waiting and the bottleneck created when demand exceeds available capacity. The westbound trips ending at La Defense business district are used to demonstrate the relative weight of the waiting time and the in-vehicle comfort on the generalized time and the paradox implied. The model is used to give some indications of the expected gains of replacing the actual one-level trainsets with more spacious duplex ones.

**Keywords:** Traffic equilibrium, Seat Capacity, Vehicle Capacity, Transit Bottleneck, Platform Stock, Wait Time, Vehicle Load, Frequency Modulation, Track Occupancy, Line Model

## 1 Introduction

The paper provides an application for the CapTA model at the line level, which serves both as a showcase of the capabilities of the model and of the finesse of the modeling approach and as a means to further investigate its behaviour. The RER A – the busiest commuter rail lines in the Paris Metropolitan Area transit network – is chosen as an application instance for the model. The transit supply stems from the 2008 data, while the demand on the line is estimated by an assignment of the same model on the Paris Metropolitan Area.

The CapTA model aims to capture the capacity phenomena related with the vehicle seat capacity, the total capacity and the interplay of passenger flows at access and egress with the dwell time and the service frequency. These phenomena are dealt with by line of operations on the basis of a set of local models yielding specific flows or costs. The sub-model of seat capacity is adapted from Leurent (2006) and Leurent (2012), where the vector of passenger flows along a service leg is faced with the available seat capacity at every stage along the route; seated alighting passengers that exit at a given station yield residual capacity, while a two level competition (with a priority for on-board standing passengers) takes places where the standing passengers among the same priority level have equal probability to get a seat. Thereafter, the in-vehicle comfort is dealt at the vehicle level.

The transit bottleneck sub-model introduced in Leurent (2011) for treating the total passenger capacity of the transit services is based on the explicit description of the passengers waiting to board a vehicle of an attractive service, constituting a passenger stock by given egress station. The passenger stock by service, faced with the vehicle's available capacity at boarding yields the probability of immediate boarding. The average waiting time on platform is similar to that of the traffic bottleneck. An interplay is established in Leurent et al (2011) between the passenger flows and the line operation at the station. Indeed, the boarding and alighting flows influence the dwell time of the vehicles of the transit services at the station. Prolonged platform occupancy of the vehicles of a transit service may lead to the accommodation time of the services at that section to exceed the reference period. Hence the frequency of all the services is modulated at departure and propagated downstream.

The effects described take place within a transit line. The topological order of the line is used to devise two line models of, respectively, flow loading and cost setting, each of which calls its local sub-models. The pair of line algorithms amounts to a complex cost-flow relationship

at the level of the line. The line model is used as a sub-model in passenger assignment to network hyperpaths, where line pairs of access-egress stations constitute leg links.

The rest of the paper is structured in seven parts and one conclusion. First, we present the initial and extracted transit network, the demand used and the services present in the RER A line, before focusing on the passenger flows on the network level. Then, we relate the dwell time and the operating frequency with the passenger exchange flows. In the fifth part, a transit service is used as an example to demonstrate the relation between the residual capacity of the service and the boarding flows and inquire on the in-vehicle comfort. Part six focuses on the formation and the behaviour of the passenger stock of different services. More precisely, the partial stock to La Defense station is extracted and related to the exogenous flow. We shed light to the relative effects of the generalized time components; the in-vehicle comfort and waiting time, before assessing the effect of the replacement of the lower capacity one-level trainsets with more spacious duplex ones.

## **2 Transit Network, Trip Demand and Supply of Services**

### **2.1 *The initial network***

The CapTA model is first applied to the transit network of the Paris Metropolitan area. The transit network is composed of 95 directional railway lines (for the guided transit modes – Train, RER, Metro and Light Rail) yielding 259 guided transit services, and 4 483 bus services. Demand at the morning peak hour involves 1,23 million trips between 1 305 travel demand zones. The network contains about 159 800 nodes and 307 700 arcs and line legs. The model was programmed in C++ and run on a 2,66 GHz PC with 4 GB of RAM. The average run time per iteration amounts to 8 minutes for the unbounded model. Each iteration in the capacitated model – extending the in-vehicle comfort also to the bus services - requires about 23 minutes. An acceptable level of convergence was reached after 30 iterations (with a duality gap reduced to 1% of the initial value).

### **2.2 *The Restrained Network - RER A Commuter Rail Line***

The results are limited, for clarity, to the RER A, the busiest commuter rail line on the network, with a daily patronage often exceeding the one million passenger threshold. The RER A line is composed of 46 stations spread on its five branches and the central trunk. Two

branches on the east (Marne-la-Vallée on the northeast and Boissy-St-Leger on the southeast) and three branches on the west (Cergy and Poissy on the northwest and St-Germain-en-Laye on the southwest) converge to the central trunk. Therefore, the east and west suburbs are connected to the centre of Paris and La Defense business district. The restrained network contains 1 200 service network nodes, while the 182 initial arcs are transformed into 1 702 line legs.

The demand on the RER A was extracted by an assignment on the entire network after 50 iterations with an OD matrix of the morning peak hour multiplied by 1,3, while considering all the capacity effects. The simulations share the same penalty coefficients for the trip components, as described in subsection 2,4. The results show about 107 000 passengers circulating eastbound, while 141 000 passengers board on the westbound direction which connects the centre of Paris with La Defense business district on the east. The RER A line totals around 248 000 passengers during a morning hyper-peak hour on both directions.

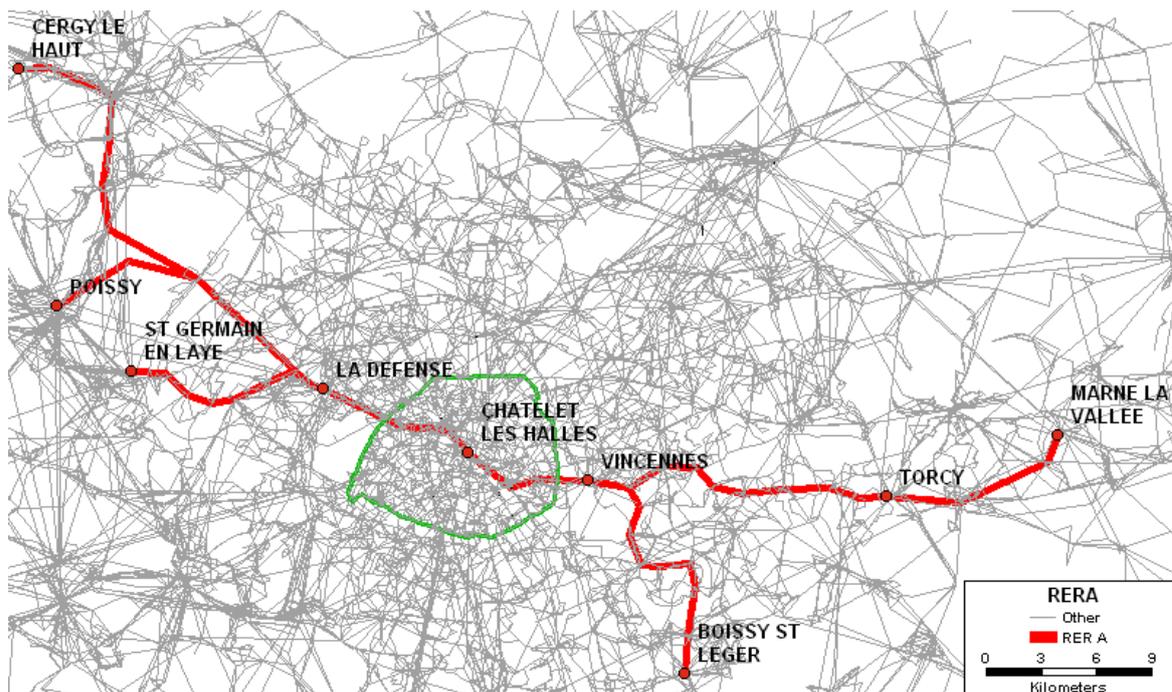
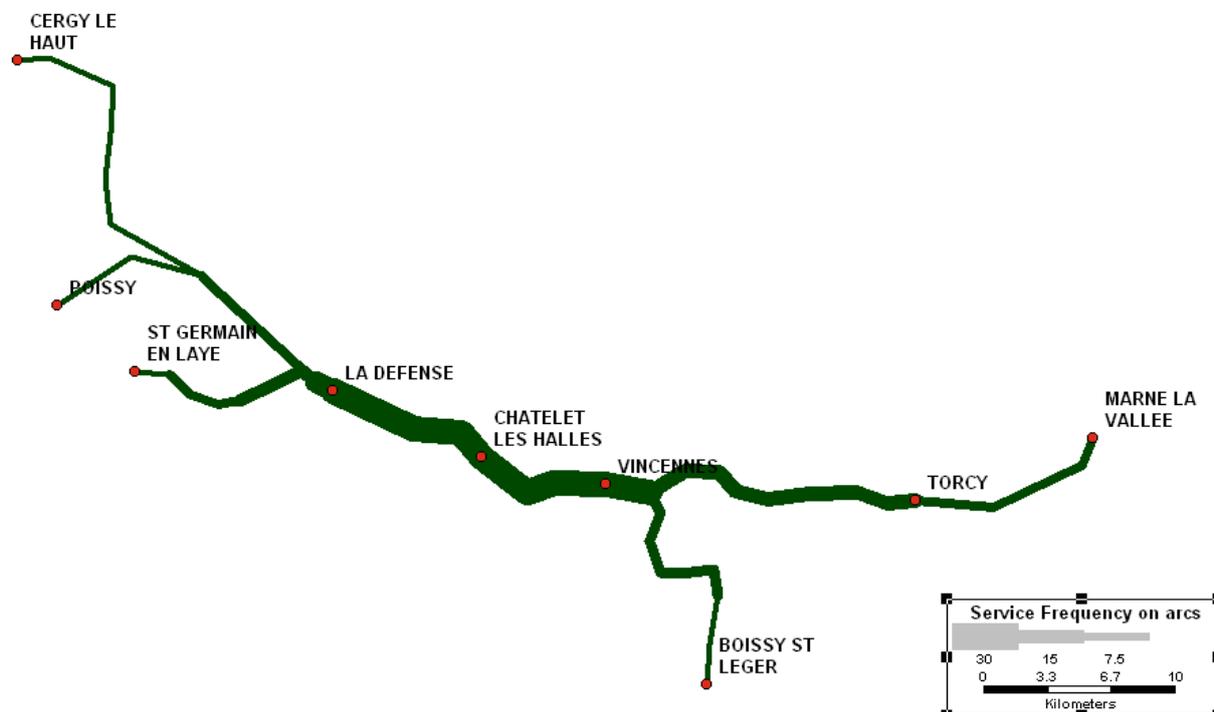


Figure 1 The RER A (red) and the rest of the transit network (grey)

### 2.3 The westbound transit supply

During the morning hyper-peak hour, the westbound transit supply is composed of 18 trains from Marne-la-Vallée (MLV) and 12 trains from the Boissy-St-Leger (BOI) branch that converge at Vincennes station (see Figure 2). Thereafter, 30 trains per hour run on the central trunk until La Defense, before diverging to the three branches, in the number of 5 for Poissy,

5 for Cergy and 16 for St Germain-en-Laye branch (4 vehicles per hour terminate at La Defense).



**Figure 2** The frequency at departure on the westbound RER A

These trains are associated with 15 different transit services, each one characterized by a scheduled frequency, a stopping policy (express, local, etc.) and a type of rolling stock, detailed in table 1. Three types of rolling stock run on the tracks of the RER A. One-level trains, such as the MS61 with 600 seats and a total capacity of 1 888 passengers per train set and the MI84 with 432 seats and a total capacity of 1 760 passengers coexist with more spacious duplex trains; the MI2N offers 1 056 seats and a total capacity per train set of 2 580 passengers. The boarding and alighting passengers are evenly distributed on flow streams, defined as the minimum width on a vehicle's door for the boarding or alighting of a single passenger, equal to 0,65 m (EgisRail, 2009). Per vehicle side, we can find 64 flow streams on the MS61, 72 on the MI84 and 90 on the MI2N.

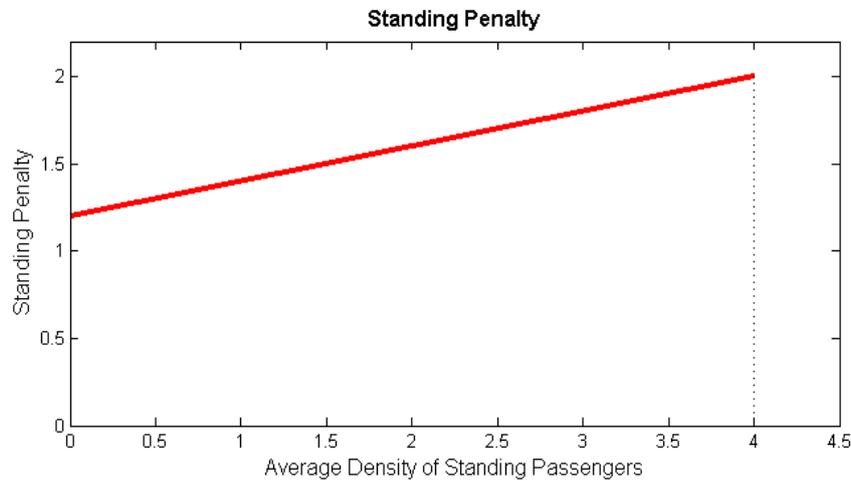
**Tableau 1 The detailed stopping policy for the westbound transit services**

Section	Transit Service Type of Vehicle Frequency (vehicles/hour)	BABY	BIPE	BROU	TATI	TEDY	THEO	TOUL	UCLA	UGIN	UNIR	UPAC	YRIS	XUTI	ZARA	ZEBU
		MI84	MI2N	MI2N	MI2N	MI84	MS61	MS61	MS61							
		1	1	2	2	1	1	1	1	1	2	1	4	5	6	1
MLV BRANCH	MARNE LA VALLEE CHES	●	○		●	○		○	●	○	○	○				
	Val d'Europe	●	○		●	○		○	●	○	○	○				
	BUSSY ST GEORGES	●	○		●	○		○	●	○	○	○				
	TORCY	●	○	○	●	○	○	○	●	○	○	○	○	○		
	LOGNES	●	○	○	●	○	○	○	●	○	○	○	○	○		
	NOISIEL	●	○	○	●	○	○	○	●	○	○	○	○	○		
	NOISY CHAMPS	●	○	○	●	○	○	○	●	○	○	○	○	○		
	NOISY LE GRAND MONT	●	○	○	●	○	○	○	●	○	○	○	○	○		
	BRY SUR MARNE	●	○	○	●	○	○	○	●	○	○	○	○	○		
	NEUILLY PLAISANCE	●	○	○	●	○	○	○	●	○	○	○	○	○		
VAL DE FONTENAY	●	○	○	●	○	○	○	●	○	○	○	○	○			
BOI BRANCH	BOISSY ST LEGER													○		○
	SUCY BONNEUIL													○		○
	LA VARENNE CHENNEVIERES													○	○	○
	CHAMPIGNY													○	○	○
	LE PARC DE ST MAUR													○	○	○
	ST MAUR CRETEIL													○	○	○
	JOINVILLE LE PONT													○	○	○
	NOGENT SUR MARNE													○	○	○
FONTENAY SOUS BOIS													○	○	○	
CENTRAL TRUNK	VINCENNES	●	○	○	●	○	○	○	●	○	○	○	○	○	○	○
	NATION	●	○	○	●	○	○	○	●	○	○	○	○	○	○	○
	GARE DE LYON	●	○	○	●	○	○	○	●	○	○	○	○	○	○	○
	CHATELET LES HALLES	●	○	○	●	○	○	○	●	○	○	○	○	○	○	○
	AUBER	●	○	○	●	○	○	○	●	○	○	○	○	○	○	○
	CHARLES DE GAULLE ETOILE	●	○	○	●	○	○	○	●	○	○	○	○	○	○	○
	GRANDE ARCHE DE LA DEFENSE	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
NANTERRE PREFECTURE	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
STG BRANCH	NANTERRE UNIVERSITE												○	○	○	○
	NANTERRE VILLE												○	○	○	○
	RUEIL MALMAISON												○	○	○	○
	CHATOU CROISSY												○	○	○	○
	LE VESINET CENTRE												○	○	○	○
	LE VESINET LE PECQ												○	○	○	○
	ST GERMAIN EN LAYE												○	○	○	○
CRG BRANCH	HOUILLES CARRIERES S				○	○	○	○	○	○	○	○				
	SARTROUVILLE				○	○	○	○	○	○	○	○				
	MAISONS LAFFITTE				○	○	○	○	○	○	○	○				
	ACHERES VILLE								○	○	○	○				
	CONFLANS FIN D'OISE								○	○	○	○				
	NEUVILLE UNIVERSITE								○	○	○	○				
	CERGY PREFECTURE								○	○	○	○				
	CERGY ST CHRISTOPHE								○	○	○	○				
	CERGY LE HAUT								○	○	○	○				
POI	ACHERES GRAND CORMIE				○	○	○	○								
	POISSY				○	○	○	○								

## 2.4 Simulation Parameters and Convergence

The generalized time is deduced by applying penalty coefficients for the various trip components denoting their relative weight. Hence, the access and egress trips and the transfer time (without the additional waiting) are multiplied by 2, as happens with the waiting time. The in-vehicle comfort makes reference to the obvious differentiation between two comfort states; travelling standing or sitting. Recent research (Debrincat et al, 2006 and TRB, 2003) implies that the in-vehicle penalty coefficient depends on the density of the standing passengers. Therefore, we adopt a linear function of the standing penalty factor  $\chi_{za}^r(d_a)$

where  $d_a$  is the density of standing passengers for a certain trip section  $a$ . The standing penalty coefficient varies from 1,2 (for  $d_a = 0$ ) to 2 (for  $d_a = 4 p / m^2$ ), while the multiplier for travelling seated is 1.



**Figure 3** The standing penalty coefficient in relation to the density of standing passengers

An acceptable level of convergence was reached after 30 iterations, with a convergence indicator reduced to 1‰ of the initial value.

### 3 Passenger Flows on the Network

#### 3.1 Passenger Flow on the line

The passenger flow throughout the restricted network is quite similar with the flows on the RER A of the initial network. Figure 4 illustrates the network passenger flows and the flow-to-capacity ration on the line. The width of the lines represents the passenger flow, while the colours (from light green to red) correspond to the ratio of the total flow on the line to the capacity of the transit services. Additional attention must be given due to the overlapping of the westbound and eastbound arcs.

As assumed, the passenger flow and the used capacity is low at the extremities of the RER A for both directions, while increasing significantly before the various branches converge to the central trunk. Indeed the flow-to-capacity ratio exceeds 75% before the convergence of the branches to the central trunk. The maximum load corresponds to the westbound interstation between the Chatelet-les-Halles and Auber stations, with 59 319 passengers. The flow

exceeds slightly the nominal capacity from Nation to Etoile at the central trunk, to reach a peak on the Chatelet-les-Halles–Auber section with 1,03 of the nominal line capacity.

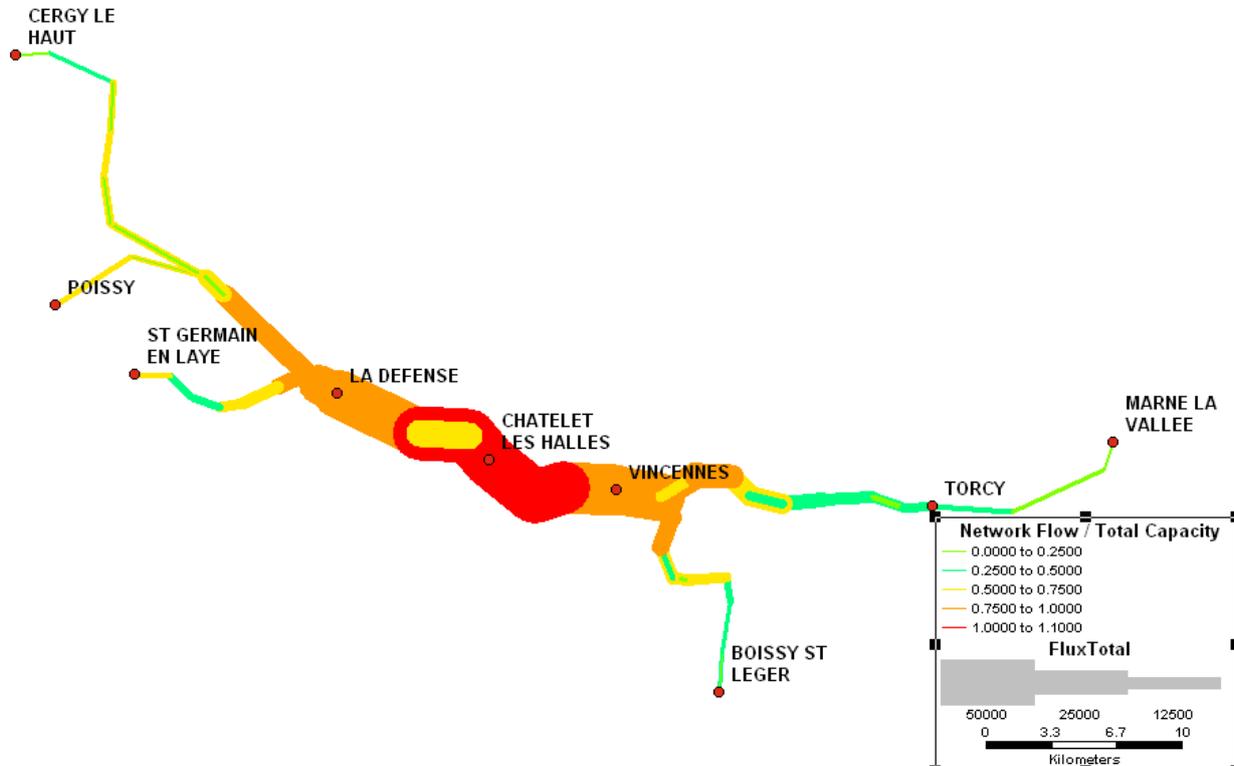
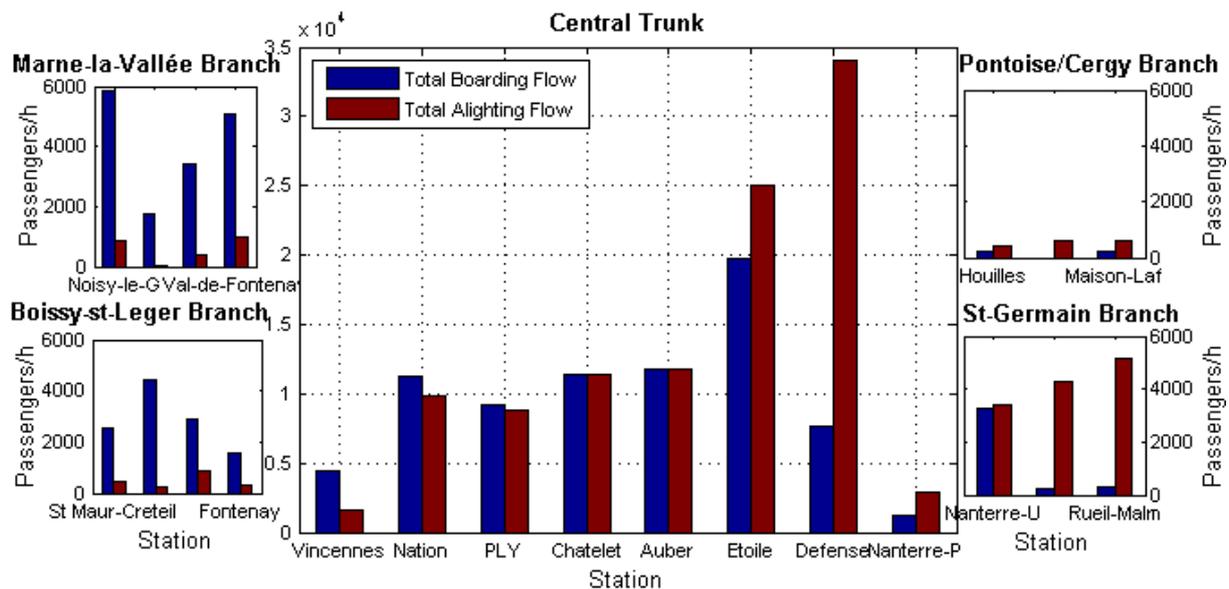


Figure 4 The passenger flow throughout the restrained RER A network

### 3.2 Boarding and alighting passengers flows

We focus our analysis on the westbound section. In Figure 5, we depict the boarding and alighting hourly flows on the busiest line section, from Noisy-le-Grand and St-Maur Creteil stations on the east to the Maison Lafitte and Reuil Malmaison stations on the west. The relation between the boarding (blue) and alighting (brown) flows in Figure 5 can be used for the sectioning of the westbound service of the line into three segments. From the east suburbs, until Vincennes, the boarding flows clearly outpace, seven times, the alighting flow. That segment acts as a feeder from the east suburbs to the centre of Paris and La Defense business district. At the central segment, from Nation until Etoile stations, the boarding and alighting flows are equal and the boarding is subject to the limited available capacity. The stations of the central trunk of the RER A act as transfer poles for the structural transit network of the Paris Metropolitan Area. The westbound service from La Defense station to the western

stations is characterized by bigger alighting flow than boarding. That is concurrent to the line topology, since the on-board passengers naturally alight when reaching the end of the line.



**Figure 5 Boarding and Alighting Flows on the busiest sections of the westbound service**

In addition, we may inquire on the size of the passenger exchange flow. At the branches the flow is limited and the boarding or alighting flows never exceed 6 000 passenger/hour. However, that is not the case for the central trunk, where the boarding and alighting flows are significant and their combined flow varies from 18 000 – 45 000 passengers/hour. Indeed, as shown a the following subsection, the passenger exchange flow saturates the capacity offered and the increased dwell times of the vehicles of the transit services on the line result in a frequency modulation downstream.

## 4 Dwell Times and Service Frequency

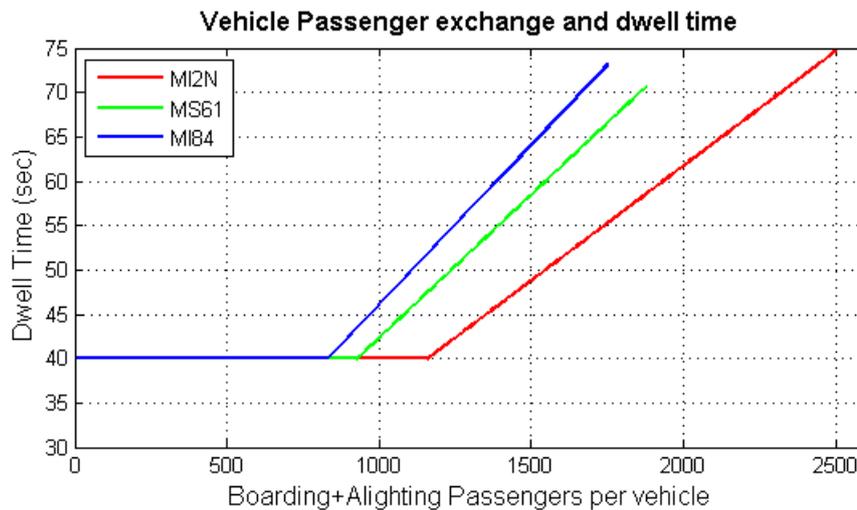
The dwell time of a vehicle is related to the passenger exchange flow per vehicle and the number of flow streams available. Its calculation considers an even distribution of the boarding and alighting flows to the available flow streams and an elementary boarding (or alighting) time per passenger (equal to 1,55 seconds/passenger) insensible to the congestion on-board and the density of the passengers present on the platform. The calculated dwell time is composed of the minimum time for the passenger exchange and the operation time – the period without passenger movement, necessary for the operation of the doors and the safe departure of the vehicle. Hence, the actual dwell time will be the maximum of the calculated

and the scheduled dwell time. That implies the existence of a critical passenger exchange flow, defined as the passenger flow for which the calculated dwell time is equal to the scheduled one. That amounts to a little less than one half of the total capacity of the rolling stock circulating on the RER A.

**Tableau 2: The characteristics of the rolling stock circulating on the RER A**

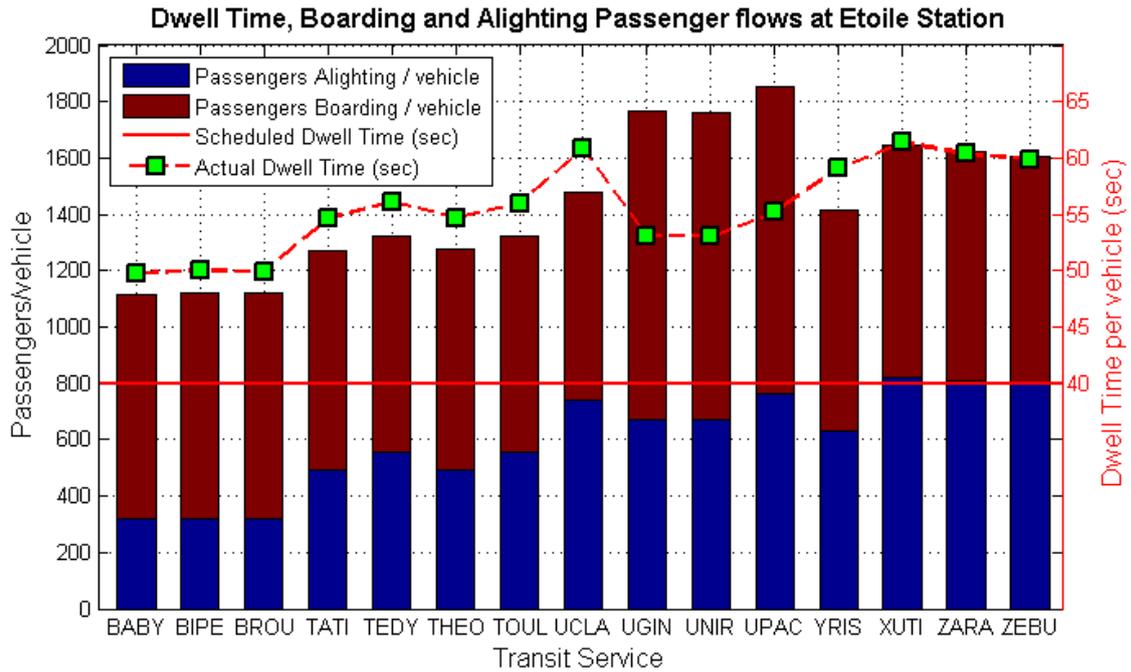
	Seat capacity (per vehicle)	Total person capacity	Nb doors	Nb of flow streams	Critical passenger flow (reduced flow streams)
MI84	432	1760	32	64	832
MS61	600	1888	36	72	929
MI2N	1056	2580	30	90	1161

The suboptimal use of the flow streams is addressed by reducing their number by 30%, and therefore we consider 43, 46 and 60 simultaneously available flow streams per vehicle side for the MI84, MS61 and MI2N vehicles respectively.



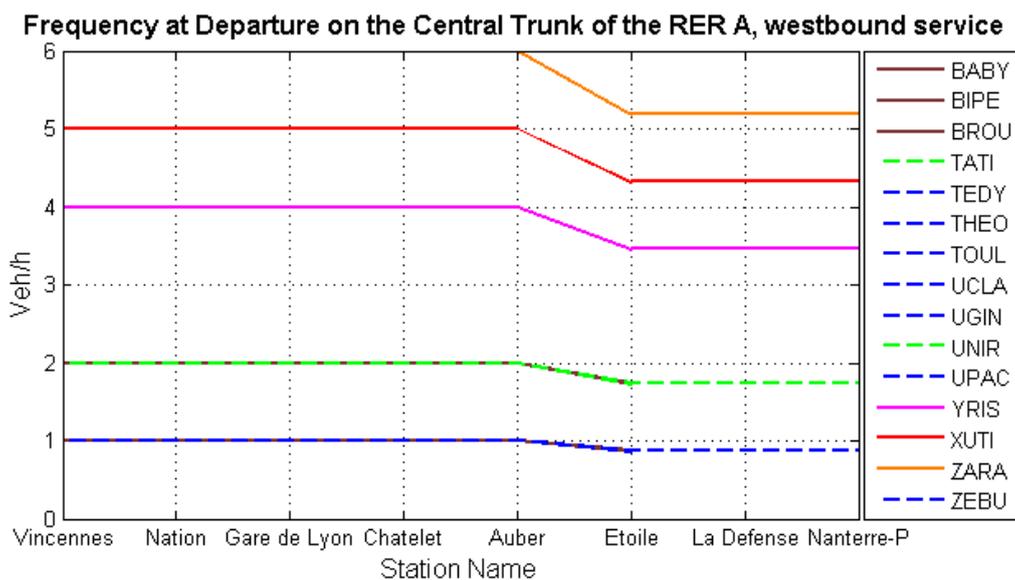
**Figure 6 Dwell Time relation on the rolling stock used in the RER A**

In the case of the westbound RER A services, the total passenger exchange flow at the Etoile station amounts to 45 000 passengers, leading to frequency modulation downstream. Depending on their characteristics, the dwell time of each service varies from 49,8 to 61,4 seconds/vehicle, higher than the 40 seconds/vehicle of the schedule, as illustrated in Figure 7. The differences in dwell time stem from the variability of the boarding and alighting flows among services and the differences of the rolling stock assigned to each service. The total exchange flow of the westbound service in Etoile is 44 804 passengers/hour with 44% alighting and the remainder boarding.



**Figure 7** Boarding, alighting passenger flows and dwell time per vehicle of the westbound services at Etoile station

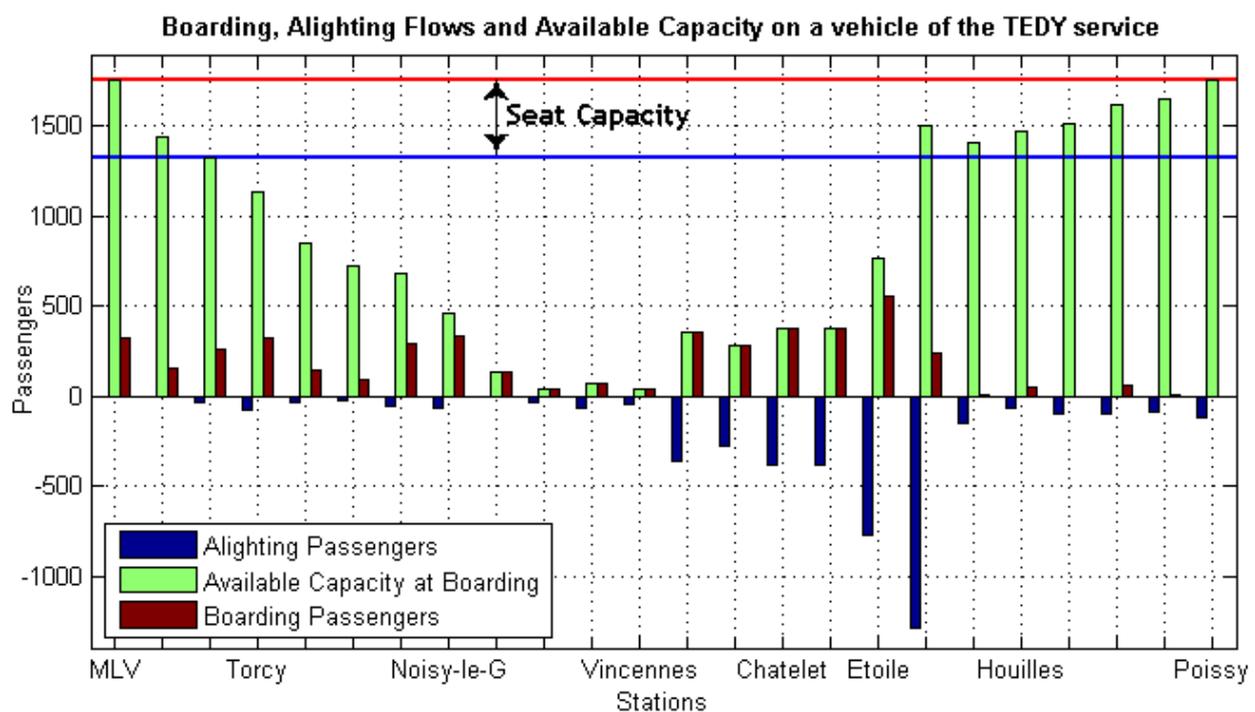
As shown in Figure 8, the combined frequency downstream is reduced by 13,6% from 30 to 25,91 veh/h, as does the capacity. However, while at La Defense the dwell time varies from 40 to 65 seconds, the frequency is not modulated, platform occupation time doesn't exceed the reference period.



**Figure 8** Frequency at departure for the westbound transit services at the Central Trunk

## 5 Residual Capacity and Boarding Flows on a vehicle

The CapTA model is characterised by strict capacity constraints at the line level (and their relaxation at the network level). Besides the competition among services, the boarding flow depends on the in-vehicle capacity available. Figure 9 illustrates the boarding and alighting process for the TEDY service (Marne-la-Vallée to Poissy). We can picture the relation between the available capacity and the boarding flow. At the beginning of the service, the available capacity is sufficient for the flow wishing to board. However, at the busiest section any available capacity comes from the alighting flow liberating space for the passengers waiting to board. We observe that at these stations the alighting flow, the available capacity and the boarding flow are equal. Therefore, when the available capacity is not sufficient, not all the passengers achieve to board, increasing the average waiting time and contributing to the formation of a passenger stock.



**Figure 9** The boarding and alighting process on a vehicle of the TEDY service

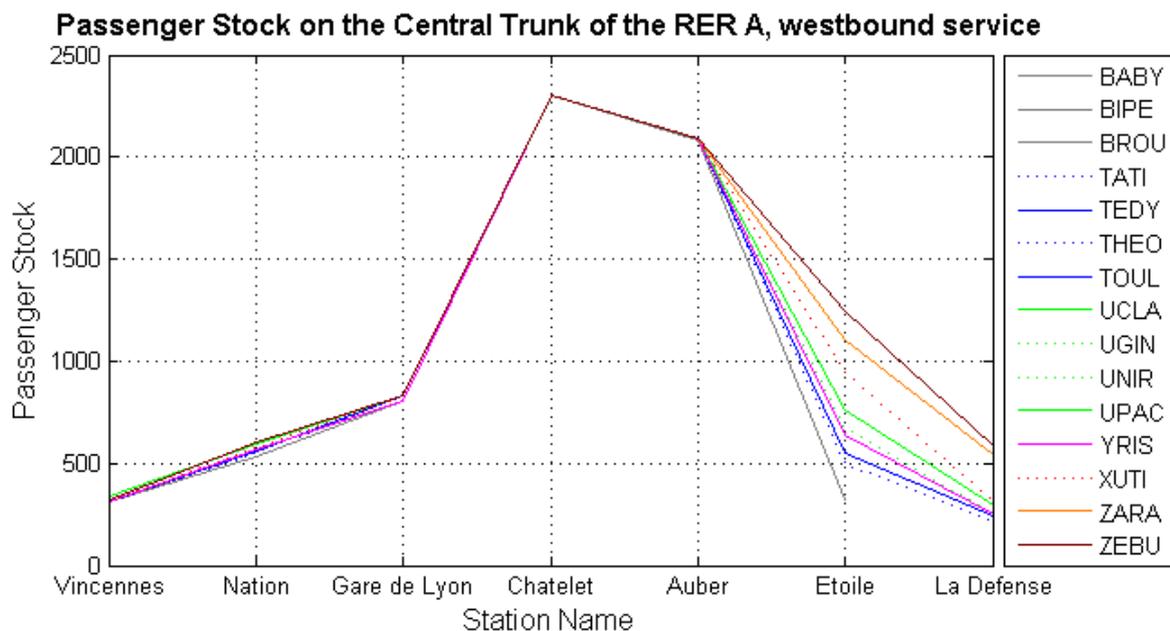
Furthermore, the area between the red and blue lines corresponds to the vehicle's seat capacity. The available capacity being inside that area means that some boarding passengers will find directly a seat. In the case of the TEDY service (as well as the other services on the MLV branch), the seats are occupied very early on the trip and no seats are available at boarding between Bussy-St-Georges (see Tableau 1 for stopping policy) and Etoile. Hence,

the boarding passengers are sure to make a part of the trip standing, while having a probability to get a seat later on their trip.

## 6 Passenger Stock and Probabilities of Immediate Boarding

### 6.1 The Passenger stock on the Central Trunk of the RER A

The transit bottleneck model, introduced in Leurent et al (2011) and formulated in Leurent (2011), is used to apprehend the effect of total capacity by explicitly describing a passenger stock. Indeed, from a given access station  $i$ , a passenger stock,  $\sigma_{is}$ , per egress station  $s$  denotes the number of passengers wishing to board any of the transit services directly connecting that couple of stations. It depends on the exogenous flow  $x_{is}$  by destination station and the available boarding capacity  $k_{zi}$  by vehicle. The passenger stock of a transit service  $n_{zi}$  is the sum of the partial stocks of all the stations called by that service  $z$ . Hence, at a given station two services with identical stopping policies downstream will have the same passenger stock, whatever their load. The vehicle inflows depend on the probability of immediate boarding  $\pi_{zi}$ .



**Figure 10: The Passenger Stock at the central section**

Figure 10 illustrates the passenger stock at boarding of the westbound transit services on the central trunk of the RER A. On the first section, from Vincennes to Auber, the boarding passengers are mainly destined to the stations of the central trunk (with an important part destined to La Defense), where the stations are called by all the services, and therefore the passenger stock is similar. However, at Etoile and La Defense stations the passenger stock varies per transit service according to their stopping policies downstream and the partial passenger stock per destination. Indeed, the passenger stock differs for the XUTI (red), ZARA (orange), and ZEBU (brown) routes which serve the St-Germain-en-Laye branch (southwest) and have different stopping pattern.

The same figure illustrates also the effect of the insufficient combined capacity of the services. When the combined capacity to evacuate the flow is sufficient but at least one service is at capacity, the passenger stock slightly increases in relation to the exogenous flow and the service's capacity to incorporate the effect of a passenger failing to board the first vehicle of an attractive service to the average waiting time. For example, at Nation, the waiting time for a trip to La Defense is associated with an actual waiting time of 3,06 minutes rather than 2 minutes for uncongested conditions. Yet, when the combined capacity is insufficient, the passenger stock explodes, since the passenger flow cannot be evacuated during the simulation period. In Chatelet, the stock reaches a value of 2 300 and is associated with an actual waiting time to La Defense of 12,09 minutes – a six fold increase from the uncongested conditions.

## **6.2 The Partial Passenger Stock to La Defense station**

We isolate the westbound trips ending at La Defense and focus on the relation between the exogenous flow  $x_{is}$  and the discharge rate  $q_{is}$ . When no congestion occurs, these values should be equal. However that is not the case, since some simplifying assumptions lead to a slight underestimation of the discharge rate, even though insignificant, varying at 1-5% according to the combined frequency of the services. On the other hand, when the combined capacity is not sufficient, as is the case in Chatelet and Auber, the difference between the exogenous flow and the discharge rate is significant, as shown on Figure 11.

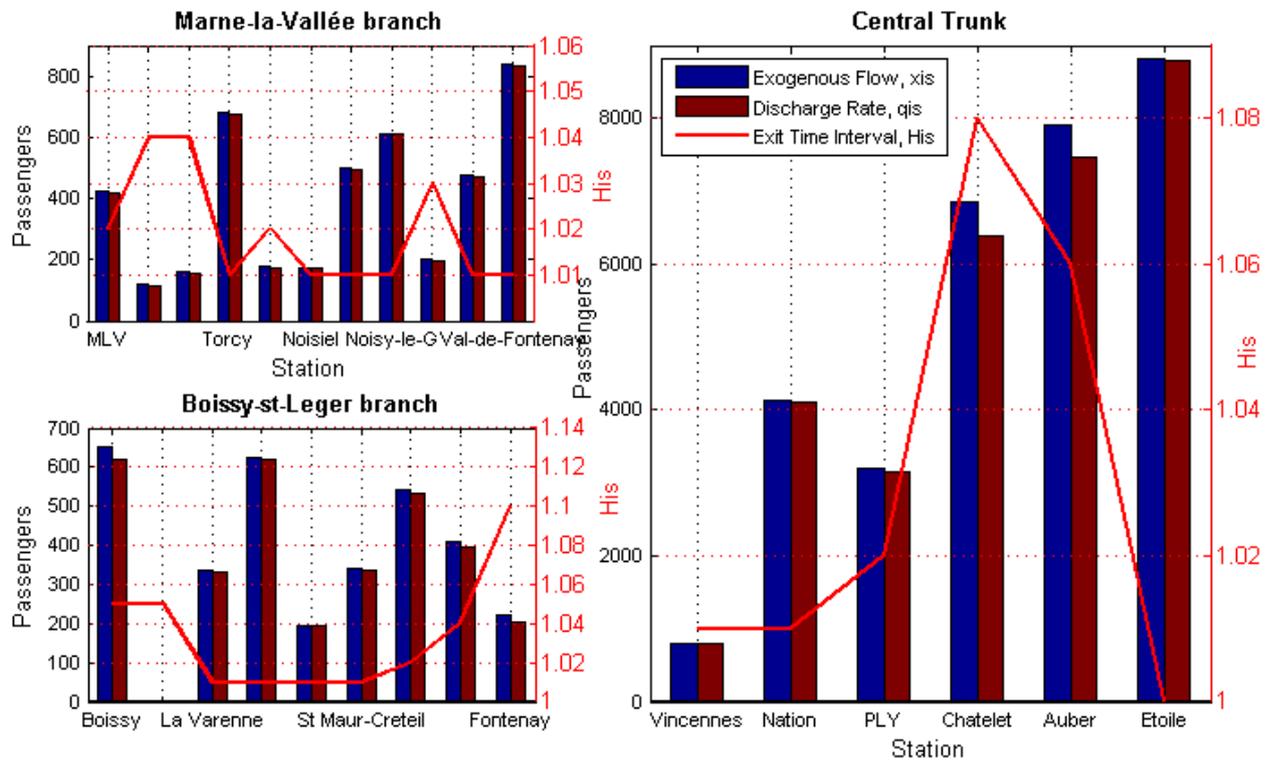


Figure 11: The exogenous flow versus the discharge rate and the exit time interval alighting at La Defense

The difference between exogenous flow and discharge rate can be expressed by the exit time interval,  $H_{is}$ ; the time needed to evacuate the passenger flow waiting to board during the simulation period. In the uncongested conditions it is slightly higher than 1, due to the non-equality between  $x_{is}$  and  $q_{is}$ , explained previously. Nonetheless, if congestion occurs, the exit time interval reflects the pressure exercised by the passenger stock at boarding. It is very surprising that in Figure 11 the highest value of  $H_{is}$  is not found at the central trunk, but rather at Fontenay station ( $H_{is} = 1,10$  at Boissy-St-Leger branch) with a low exogenous flow, since the limited frequencies and low available capacity offered make the evacuation of the passengers present to take longer.

### 6.3 Boarding Flows and route proportions

The flow boarding a certain vehicle of a transit service depends on the vehicle's residual capacity after alighting and the passenger stock of that service. In addition, the probability of immediate boarding ( $\pi_{iz} = \max\{1; k_{zj}/n_{zj}\}$ ) acts as the interface between the history of the

service – which defines the vehicle load at arrival and the available capacity  $k_{zi}$  – and the downstream stopping policy – which designates the passenger stock,  $n_{zi}$ .

**Tableau 3 Boarding Flows for the unbounded and capacity assignment**

<b>Transit Service</b>	<b>Frequency (veh/h)</b>	<b>Route Proportions with Capacity</b>	<b>Route Proportions for Unbounded</b>	<b>% difference</b>
<b>BABY</b>	1	3,20%	3,08%	4%
<b>BIPE</b>	1	2,93%	3,08%	-5%
<b>BROU</b>	2	6,68%	6,16%	8%
<b>TATI</b>	2	5,86%	6,37%	-8%
<b>TEDY</b>	1	3,16%	3,24%	-2%
<b>THEO</b>	1	3,31%	3,18%	4%
<b>TOUL</b>	1	3,13%	3,24%	-3%
<b>UCLA</b>	1	2,93%	3,56%	-18%
<b>UGIN</b>	1	5,31%	3,54%	50%
<b>UNIR</b>	2	10,61%	7,09%	50%
<b>UPAC</b>	1	4,14%	3,56%	16%
<b>YRIS</b>	4	16,73%	13,14%	27%
<b>XUTI</b>	5	12,65%	16,59%	-24%
<b>ZARA</b>	6	16,88%	20,71%	-18%
<b>ZEBU</b>	1	2,47%	3,45%	-28%
<b>TOTAL</b>	<b>30</b>	<b>100%</b>	<b>100%</b>	

Even though we have seen that the transit services with identical stopping policies downstream have the same passenger stock, their boarding flow, and in extent their routing proportions – depends on that available capacity,  $k_{zi}$ . Let us focus on the westbound service at the Nation station. By comparing the route proportions of the capacitated and the unbounded model, we observe differences which range from -28% to +50%, according to the services' characteristics. Indeed, the UGIN and UNIR services increase their share on the boarding flow from 3,54% and 7,09% to 5,31% 10,61%, respectively, since they have sufficient capacity to accommodate the flow failing to board other services (see figure 7) and a probability of immediate boarding equal to one.

Having identified the partial stock of the Nation – La Defense station couple, we can disaggregate the boarding flows of the services per destination, illustrated in Figure 12. The boarding flow destined to La Defense (in blue) and the miscellaneous (in brown) compose the total boarding flow, opposed to the service's available capacity (in green). The red squares correspond to the stock's probability of immediate boarding (right axis). Due to the vehicle's intrinsic characteristics and the destination competition, we observe that the boarding flow to

La Defense is not evenly distributed along the services. It varies according to probability of immediate boarding.

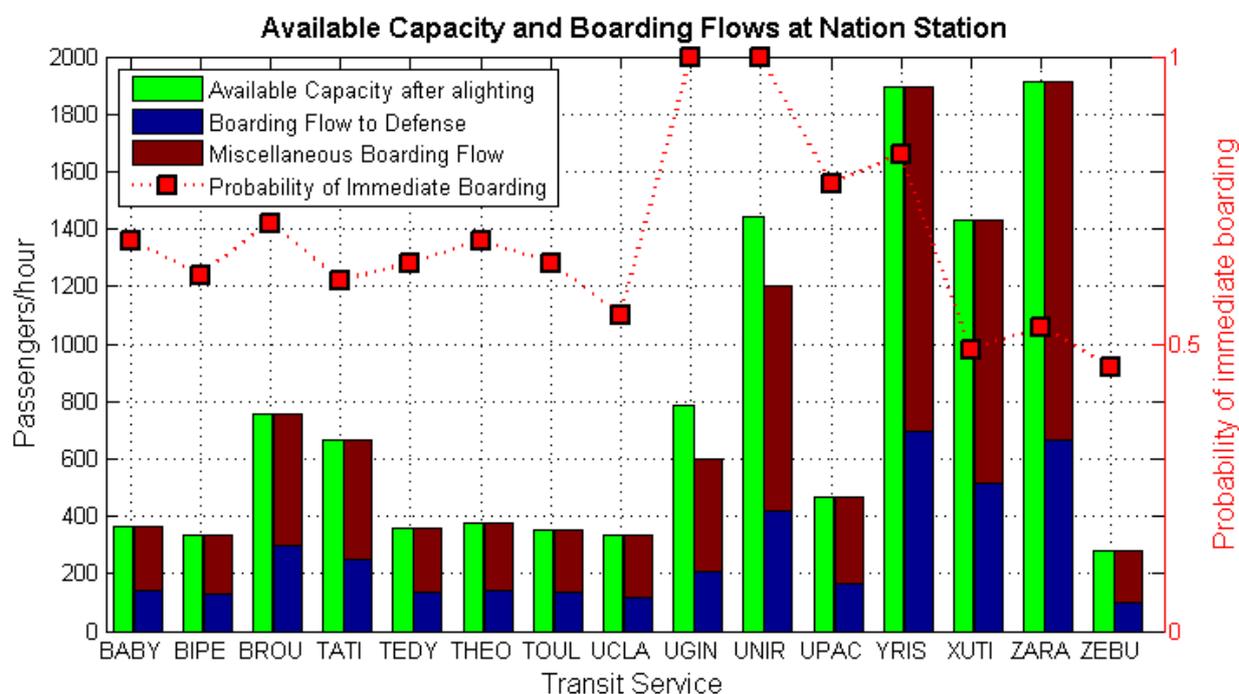


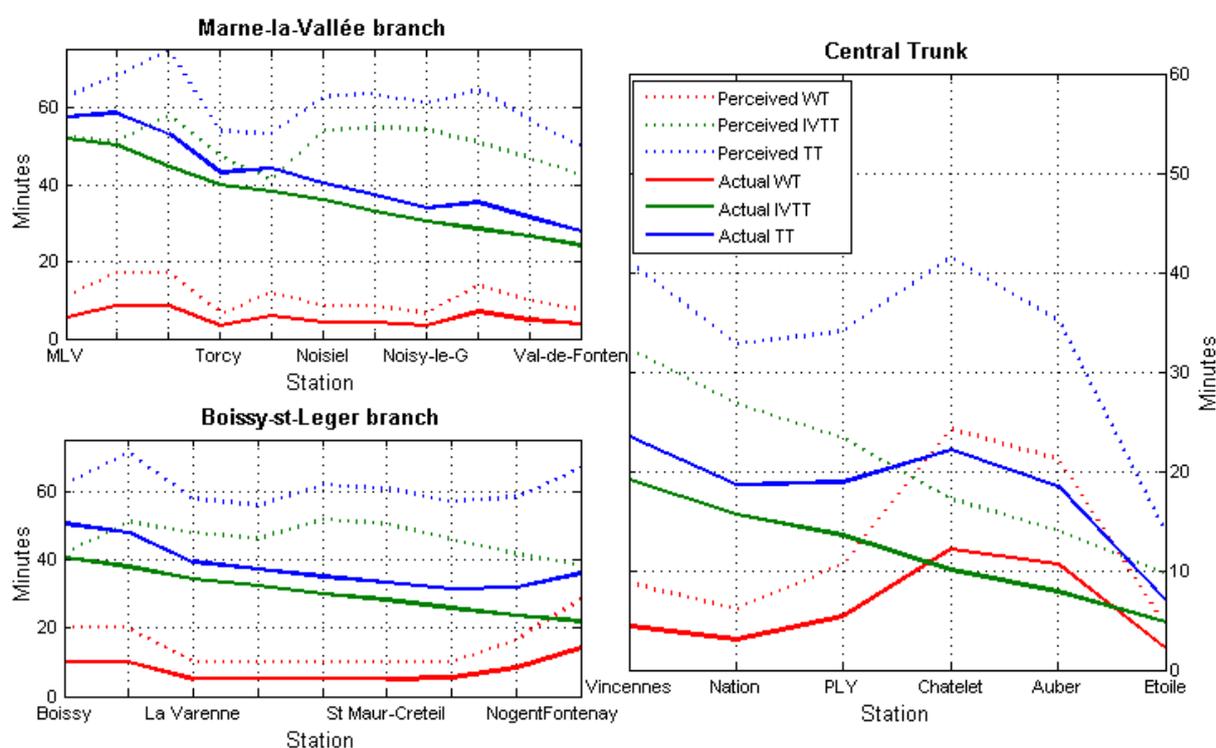
Figure 12: Route Proportions at boarding and Probability of Immediate Boarding at Nation

## 7 Average Generalized Cost

The average generalized cost for both directions on the RER A line includes the in-vehicle travel time (depending on the comfort level) and the platform waiting. We compare the total travel time and its components of the unbounded model with the capacitated model – including the three types of capacity constraints simulated in the CapTA model. The average travel time of a trip is 34,05 minutes for the capacitated model, an increase by 41% from the unbounded benchmark (24,16 minutes). That increase can be attributed for 1/3 to the increase of the perceived waiting time and for 2/3 to the increase on the perceived in-vehicle travel time due to the less comfortable states suffered by the passengers on-board. In addition, the difference of the actual travel time between these models is attributed to the waiting time.

The effect of the waiting time and the in-vehicle comfort on the travel time can be apprehended by Figure 13, illustrating the actual (continuous line) and the perceived (dotted line) travel time of the trips ending at La Defense from the east: the stations on the Marne-la-Vallée branch, the Boissy-St-Leger branch and the central trunk. The actual in-vehicle travel time (IVTT, in green) naturally decreases when approaching La Defense. The perceived IVTT

– including a penalty coefficient related to the level of comfort and the probability to occupy a seat later – is equal to the actual IVTT at the origin of the branches, where it is still possible to find directly a seat. Nevertheless, as the flow increases, so does the gap between the actual and perceived IVTT, the latter being 40-70% higher of the former. On the other hand, the waiting time (in red) stays low on the branches, compared to the IVTT, as the passenger congestion is limited, demonstrating the relative weight of each travel time component. While the increase remains limited, on the end of the branches and the central trunk, it is at Chatelet and Auber the that waiting time explodes – reaching 12 and 11 minutes respectively – due to the insufficient combined capacity of the services stopping at La Defense.



**Figure 13** The average generalized time of the trips ending at La Defense station

The total travel time (TT, in blue) of a trip from the access stations on the east to La Defense, on the west, is characterized by a travel time paradox. The actual travel time decreases naturally while approaching the destination and offering more frequencies. However, the generalized travel time, considering the effect of the in-vehicle comfort and the passenger congestion at boarding, oscillates around 60 minutes on the branches and can even increase for the downstream stations. A more astonishing situation happens on the central trunk, where a passenger boarding an upstream station, such as Nation (actual TT 18 minutes), associates his trip with a smaller actual travel time than one boarding at Chatelet (21 minutes).

## 8 The impact of a new rolling stock

As a means to deal with the saturation of the RER A, the transport authority (STIF) and the transit operator (RATP) of the Paris metropolitan area decided to invest 2 billion euros for the complete replacement of the one-level trains on the RER A, MS61 and MI84 by 130 duplex trainsets, the MI09 (Le Monde, 2012). The new train is very similar to the actual duplex, MI2N, and offers 948 seats for a total capacity of 2 600 passengers/vehicle (RATP, 2011). Therefore, the line will see a significant increase on its nominal capacity by 30% to be able to carry about 77 000 passengers per hour and direction. The architecture of the model allows taking into consideration the changes in the level of comfort and the additional capacity offered, while the service remains stable.

Applying CapTA model at the line level shows that the effects of the replacement of all one-level trainsets with the new duplex MI09, are quite significant. In fact the capacity offered is sufficient to carry all the transport demand during the morning peak hour. However, that does not apply for the passenger capacity exchange since the boarding and alighting flows in Etoile lead to a reduction of the combined frequency by 3% (as opposed with -13.6%). The average travel time per trip on both directions is reduced by 17% to 28.2 minutes. In order to consider its global effect, we estimate that the reduction of the total travel time for all the passengers during the morning peak hour is around 24 150 hours. By multiplying the peak hour gain by 5 to deduce the entire day and by 250 for a year, we estimate a conservative annual gain of 30,2 million hours per year. With a value of time at 10€/hour, the replacement of the one-level trains will bring a 302 million € socio-economic benefit.

Even though that estimation unveils the evident socio-economic benefit of the project, these indications should be taken with extreme caution since some mutually excluding effects are not considered. First the current assignment does not take into account the network effect since the new travel conditions on the RER A may attract new passenger flows, inducing additional discomfort on the line, but easing the congestion on other lines of the network. In addition, these values correspond to the 2008 situation and not to a more saturated transport demand in medium term, if no investment is made. Finally, the operational benefits are not taken into consideration, although the new trainsets boast a reduction by 31-55% of the energy consumption per passenger from the rolling stock it will replace.

## 9 Conclusion

This paper offered a realistic application instance of the CapTA model, reproducing the RER A line, the busiest commuter rail line in the Great Paris transit network, with a patronage exceeding one million passengers daily. The service network used for the application instance is an extraction of the complete transit network, while we assume that each station is connected to only one origin – destination centroid. The demand corresponds to the reconstructed passenger flows in the line after a simulation on the entire network with all the capacity constraints considered. Its original matrix is multiplied homogeneously by 1,3 as a way to approach the conditions of the hyperpeak within the morning peak hour and to provide a heavy initial load that would induce the capacity effects we analysed.

Some obvious and counter-intuitive points on the westbound service on RER A are highlighted. Even though the Chatelet – Auber is the busiest section, with 59 300 passengers/hour, the passengers exchange seems insufficient at Etoile. Indeed, the vehicle's dwell time greatly exceed the scheduled 40 seconds, resulting in a frequency modulation and a loss of capacity downstream by 13,6%. The seats are occupied early on a vehicle's trip and some saturation appears before the convergence of the branches to the central trunk. As result of the heterogeneous stopping policies and rolling stock of the transit services, the flow is not uniformly distributed among the services, some being saturated while other offering available capacity, which in turn affects the waiting time of the passengers on the platform. Taking La Defense business district as a destination, the previous effects lead to a generalized trip time which oscillates around 60 minutes at the branches – whatever the access station is – and an actual trip time which paradoxically may even increase as we approach the destination, if we compare a trip started from Nation (18 minutes) to one from Chatelet (21 minutes).

By integrating these capacity effects to the CapTA model, we may proceed to conservative estimations of a project which would offer greater capacity, without changing the service timetable. Indeed, in the case of the replacement of the actual old one-level trainsets on the RER A by more spacious duplex ones, the model brings sufficient evidence to back up a cost benefit analysis and implies a yearly gain of 30,2 million hours.

However, some modelling issues appear for further research. In the current assignment model, we adopted a comfort multiplier which ranges from 1,2 to 2, according to the average density of the standing passengers. We agreed to the hypothesis of a gradual increase of the comfort penalty due to the on-board conditions. However we do not differentiate between the waiting

time linked with the random arrival of the next vehicle and the quasi-deterministic waiting in a saturated platform. Furthermore, when the capacity available is insufficient at boarding, the passenger stock willing to board explodes along with the expected waiting time while the probability of immediate boarding plummets. That situation could designate a sort of pressure exercised at the boarding stock to board the vehicle. In other words, that could lead into an overcrowding acceptance, where the boarding flow exceeds the available capacity at boarding and the vehicle load exceeds its nominal capacity (considering 4 standing persons per available  $m^2$ ). An increased passenger load will worsen the level of comfort perceived by the passengers already on-board.

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