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1 The transportation sector and low-carbon growth pathways:
2 modelling urban, infrastructure
3 and spatial determinants of mobility

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1 The transportation sector and low-carbon growth pathways:
2 introducing urban, infrastructure and spatial determinants
3 of mobility in an E3 model

4 **Abstract**

5 There is still a controversy as to the effect of spatial organization on CO₂ emissions. This
6 paper contributes to this debate by investigating the potentials offered by infrastructure
7 measures favoring lower mobility in the transition to a low-carbon economy. This is done by
8 embarking a detailed description of passenger and freight transportation in an energy-
9 economy-environment (E3) model. In addition to the standard representation of transport
10 technologies, this framework considers explicitly the “behavioural” determinants of mobility
11 that drive the demand for transport but are often disregarded in mitigation assessments:
12 constrained mobility needs (essentially commuting) imposed by the spatial organization of
13 residence and production, modal choices triggered by installed infrastructure and the freight
14 transport intensity of production processes. This study demonstrates that the implementation
15 of measures fostering a modal shift towards low-carbon modes and a decoupling of mobility
16 needs from economic activity significantly modifies the sectoral distribution of mitigation
17 efforts and reduces the carbon tax levels necessary to reach a given climate target relatively to
18 a “carbon price only” policy. This result is robust to a wide range of assumptions about
19 exogenous parameters.

20 *Keywords:* transport, mitigation policy, infrastructure, spatial organisation

21 *JEL:* C68, O18, R40

22

1 **1 - Introduction**

2

3 Curbing emissions in the transportation sector is a major issue for any ambitious climate
4 policy. Carbon emissions from transport activities have indeed experienced a fast growth
5 (+44% over the past two decades) to reach 22.5% of all energy-related (IEA, 2011a), and are
6 expected to pursue this trend in the future (for example,(IEA, 2011b) predicts a further
7 increase by one-third by 2030). This trend is not incompatible with ambitious climate policies
8 as long as the reductions of global emissions can be obtained by exploiting low-cost
9 mitigation potentials in residential, industry and power sectors (IPCC, 2007, Figure SPM6).
10 But, at a long-term horizon, the drastic reduction of carbon emissions made necessary by
11 low stabilization targets cannot be reached without controlling also transport-related
12 emissions.

13 A large body of literature explores mitigation options and policies in the transport sector and
14 emphasizes that ambitious reductions in the transport sector would require actions on both
15 the “technology” side to decrease both the energy intensity of transportation modes and the
16 carbon content of fuels, and on the “behaviour” side to reduce the volume of mobility and
17 foster the adoption of low-carbon modes. This diagnosis contrasts with existing analyses of
18 the transport sector with energy-economy-environment (E3) models, which are useful tools
19 to investigate the role of transportation in the transition to a low-carbon economy, given the
20 important interactions between transportation and the rest of the economy. However, these
21 approaches remain limited to explore the full mitigation potentials of the transport sector
22 because they have essentially focused on the assessment of the “technology” side (e.g.
23 Schafer et al., 2009). To provide a more comprehensive vision, these tools have to be

1 complemented with representation of the “behavioural” determinants of transportation
2 dynamics (Schafer, 2012).

3 This paper is an attempt to bridge the gap between studies of mitigation options and policies
4 in the transport sector and E3 models. It first reviews the literature on climate policies and
5 the transportation sector, to delineate the determinants and obstacles to CO₂ emissions
6 reduction in that sector (section 2.1) and emphasize the potential role of policies on the
7 “behaviour” side of transportation dynamics (section 2.2). Section 3 describes how stylized
8 representations of the “behavioural” determinants are introduced in the E3 model Imaclim-
9 R (Waisman et al., 2012) to explicitly represent the interplay between transportation, energy
10 and growth patterns when accounting for the rebound effect of energy efficiency
11 improvements on mobility, endogenous mode choices in relation with infrastructure
12 availability, the impact of investments in infrastructure capacity on the amount of travel, and
13 the constraints imposed on mobility needs by firms’ and households’ location. This
14 framework is then used in Section 4 to assess the role of transportation in low-carbon
15 pathways.

16 This analysis demonstrates the risk of high losses if using carbon price as the sole
17 instrument, and investigates the potentials offered by richer combination of measures.
18 Complementarily to carbon pricing, this study considers more specifically actions to control
19 the “behavior” determinants of transportation in the course of the low-carbon transition,
20 including (i) spatial reorganizations at the urban level and soft measures towards less
21 mobility-dependent agglomerations, (ii) reallocation of investments in favor of public modes
22 at constant total amount for transportation infrastructure and (iii) adjustments of the
23 logistics organization to decrease the transport intensity of production/distribution
24 processes and optimize the use of vehicles. This analysis provides a first step towards the

1 identification of non-energy determinants of global mitigation costs and concludes with a
2 roadmap for further integrating transportation, housing and urban dynamics issues into
3 macroeconomic assessment of climate policies.

4 .

5 **2 - Climate policies and the transportation sector**

6 **2.1 Determinants and obstacles of carbon emission reductions in the transport sector**

7 As it is standard in climate analyses, we decompose transport carbon emissions along its
8 four essential determinants: the carbon intensity of fuels, the energy intensity of mobility,
9 the modal structure of mobility and the volume of mobility. Following Chapman (2007) and
10 Schafer (2012), the first two determinants can be labeled as “Technology”, while the last two
11 can be labeled as “Behaviour”.

12

13 **Technology**

14 The *carbon intensity* is dependent on the primary sources used to produce the final energy
15 used to fuel vehicles. Today, the vast majority comes from oil refining, but anticipations of
16 resource depletion and oil price increases make credible the large-scale diffusion of other
17 sources at a medium-term horizon. The decrease of fuels’ carbon intensity then crucially
18 depends on the potential of low-carbon processes for liquid fuel supply (biofuels) and on the
19 diffusion of alternative energy carriers (electricity and hydrogen). All these low-carbon
20 options are faced with intrinsic limitations.

21 Biofuels raise three types of concerns, which may limit their large scale diffusion. First, the
22 technical potential of biomass production remains controversial and difficult to characterize

1 due to large uncertainty on yield improvements, the production potential of degraded land
2 and climate change feedbacks (Chum et al., 2011). Second, the lifecycle impact of biomass
3 on GHG emissions may be less beneficial than expected with respect to conventional fuels,
4 depending on the use of fertilizers, the input of fossil fuels in the production, transport and
5 conversion of biomass, as well as on how land use is affected by the biomass production (see
6 Searchinger et al., 2008; Tilman et al., 2009). Third, large scale biomass production is
7 submitted to land-use and water-use competition with other usages and objectives like food
8 provision, timber production or forest conservation. Nuclear and renewables, the main
9 carbon-free power technologies, are limited by political acceptability and intermittency,
10 respectively. Competitive and safe hydrogen storage systems with the appropriate end-user
11 infrastructure face important technological obstacles. Put together, all these obstacles
12 highlight the risk that the supply of long-term end-use energy for transport may rely
13 importantly on particularly carbon-intensive options (non-conventional oil, gas-to-liquids
14 and coal-to-liquids) driving fastly growing trends of these sources to reach 7.4 mb/d in 2030
15 according to IEA projections (IEA, 2011b)

16 The *energy intensity of mobility* results from the technical characteristics of the vehicle fleet
17 for which improvements may be limited by asymptotes on technical progress of drive train
18 efficiency and inertias on the deployment of new energy-efficient vehicles. Indeed, the
19 market potential may be only a fraction of its economic potential if, under partial
20 information and imperfect foresight about the future of energy costs (Allcott, 2010;
21 Anderson et al, 2011; Allcott, 2011), purchase decisions under-value or even ignore future
22 energy savings of vehicle efficiency (Greene, 1998; Turrentine and Kurani, 2007) and are
23 importantly influenced by other considerations than energy consumption (e.g., safety,
24 performance, size). Standards have proven efficient to foster the diffusion of more carbon

1 efficient vehicles (around 140gCO₂/km), but their effect at more stringent constraints may
2 be limited in absence of clear price-signals allowing an appraisal of long-term benefits in
3 terms of energy savings.

4 **Behaviour**

5 The *modal structure of mobility* breaks down between carbon-intensive options (air,
6 passenger cars, trucks) and low-carbon ones (public transport and non-motorized modes for
7 passengers; rail, shipping and inland waterways for freight). The promotion of the latter
8 group requires dedicated investments in infrastructures for public modes to improve their
9 coverage, speed, reliability and flexibility. Yet, in absence of intermodal synergies,
10 cumulative mechanisms such as positive network externalities often make it cheaper to
11 expand one network instead of maintaining two in parallel (e.g., rail + road), especially when
12 accounting for inertias in the renewal of long-lived infrastructures. Therefore path-
13 dependencies and lock-ins in energy-intensive mobility options may arise.

14

15 The *volume of mobility* results from households' tradeoffs between passenger transport and
16 the demand for other goods under budget and time constraints, as well as firms' freight
17 mobility needs in the production/distribution process. These decisions are constrained by
18 the interplay between four effects, each of them imposing inertia on the dynamics of
19 mobility. First, passenger daily commuting distances and the transport intensity of
20 production are defined by the spatial distribution of housing, transport and industrial
21 infrastructures, which are long-lived and hence characterized by strong inertias. Second,
22 location choices, and hence mobility needs, are decided in function of a tradeoff between
23 transport and housing expenditures. The decrease of transport prices in real terms (ie with

1 respect to income) combined with an increase of housing prices are at the root of urban
2 sprawl triggering a rise of mobility needs (Brueckner, 2000). These trends could be reversed
3 only if the dynamics of transport and housing sectors are reversed. Third, in line with the
4 seminal work by (Zahavi and Talvitie, 1980) confirmed by more recent studies (Metz, 2008;
5 Schäfer et al, 2009; Schäfer, 2012), households are conventionally assumed to devote a
6 given time to mobility so that speed gains permitted by infrastructure deployment may give
7 rise to increased distances (longer daily travels and more occasional trips) and modal shifts
8 (in favor of fast modes within the time constraint, like aviation). Finally, the tradeoff
9 between inventories and just-in-time organizations decides the logistics organization and in
10 particular the total vehicle-kilometers travelled for the production/distribution of a given
11 volume of goods (McKinnon, 2010; Piecyk and McKinnon, 2010).

12 Moreover, two well-known feedback effects apply to the volume of mobility (Hymel et al.,
13 2010). On the one hand, the “induced demand effect” (Goodwin, 1996) is a response to
14 infrastructure building or improvement, which may trigger an increase of mobility because
15 of enhanced accessibility or improved services provided by a given mode. In the long run,
16 enhanced accessibility also changes the economic value of land, affecting the locations of
17 activities and housing and hence mobility needs (Noland, 2008). The influence of the
18 “induced demand effect” on CO₂ emissions is described in Shalizi and Lecocq (2009) for the
19 case of the US Interstate Highway. On the other hand, the “rebound effect” captures the
20 increase of mobility consecutive to reductions of the marginal costs of travel permitted by
21 fuel economy under improved efficiency (Greening et al, 2000). The magnitude of this effect
22 can be very significant: for instance, Wang et al. (2012) estimate that the average rebound
23 effect for passenger transport by urban households is around 96%, indicating that the

1 majority of expected reduction in energy consumption (and CO₂ emissions) from efficiency
2 improvement could be offset.

3

4 This general picture illustrates that changes in transportation patterns are driven by other
5 crucial determinants than energy prices such as income, the spatial organization, housing
6 costs and transport infrastructure availability.

7

8 **2.2 Mitigation policies in the transport sector**

9 A very large literature explores mitigation options and policies in the transport sector at
10 different spatial scales. The most recent publications include studies at the global scale (e.g.
11 IEA, 2009; Schafer et al., 2009; Johansson, 2009), at the regional level (e.g. Banister, 2000 for
12 Europe), at the national scale (e.g. Bristow et al., 2008, for UK; Akerman and Hojer, 2006, for
13 Sweden; Mc Collum and Yang, 2009, and Greene and Plotkin, 2011 for US) and at the city
14 scale (e.g. Hickman et al., 2010 for London; Hickman et al., 2011 for London and Delhi). All
15 these studies share the conclusion that technologies (reducing the carbon intensity of
16 energy and the energy intensity of transport modes) will play a major role. However, the
17 majority of studies also conclude that actions on the modal structure and volume of mobility
18 (grouped under the label “behavior”) will be required; the extent of these actions depending
19 on the technological optimism of the study.

20 Besides the issue of the relative importance of actions on the “technology” side vs. actions
21 on the “behavior” side, the question of the policy instruments to trigger emissions
22 reductions is central.

1 **2.2.1 Price signals, energy demand and carbon emissions**

2 A crucial specificity of the transportation sector is that demand for transportation services,
3 and fuel consumption from vehicles appear weakly sensitive to energy prices. This appears
4 clearly in (Goodwin et al. 2004), who estimate a low value of short-run price elasticities for
5 the traffic volume (-0.1) and fuel consumption (-0.25). The higher short-run price elasticity
6 for fuel consumption than for the traffic volume captures that unitary fuel consumption per
7 miles traveled can decrease even in the short-term thanks to a more efficient use of
8 vehicles, including eco-driving.¹ This study also demonstrates that price elasticities are
9 greater by factors of 2–3 over five-year periods, but also that income elasticities are greater
10 than price elasticities by factors of 1.5–3. These general conclusions are confirmed by more
11 detailed recent analyses. By distinguishing econometric estimates of long-run price
12 elasticities for gasoline and diesel demand, for different price and income levels and for 120
13 countries, (Dahl, 2012) obtains that price elasticities range between -0.11 and -0.33, and
14 between -0.13 and +0.38 for gasoline and diesel respectively, while income elasticities are
15 much higher (between +1.26 and +0.66 for gasoline and around +1.34 for diesel). This means
16 that, even at a long term horizon, fuel consumption reductions triggered by price increases
17 may be offset by wealth effects, especially in fast growing economies.

18 This review demonstrates that only a sustained increase of price signals in the very long run
19 is likely to affect significantly transport-related carbon emissions. However, only high carbon
20 prices would trigger a notable increase of fuels' end-use price. For instance a price of carbon
21 of 40-100 \$/CO₂—in the very high range of what is currently considered feasible at large
22 scale—would translate in a moderate 0.35–0.90 \$ per gallon increase in gasoline cost.
23 Looking forward, the IPCC thus estimate that multiplying the price of carbon by 5 in 2030

1 (from 20\$/tCO₂ to 100\$/tCO₂) would only induce a 23% decrease of transport-related carbon
2 emissions (IPCC, 2007).

3 **2.2.2 The role of mobility-control measures**

4 A direct implication from the above review is that, under a “carbon-price-only policy”,
5 substantial mitigation in the transportation sector can be reached only through very high
6 carbon prices. This diagnosis is confirmed by studies on marginal abatement costs curves in
7 the transport sector compared to other sectors, which demonstrate that mitigation options
8 in the transport sector are mainly towards the right of MACCs, i.e. with high carbon prices
9 (e.g. UK Committee on Climate Change, 2008; Smokers et al., 2009). The concerns raised by
10 the political acceptability and the economic consequences of such high carbon prices lead to
11 consider the role of complementary measures that aim at controlling transport-related
12 carbon emissions through specific actions.

13 Number of measures can be envisaged to decrease the carbon intensity and/or the energy
14 intensity determinants of carbon emissions, but all of them are submitted to constraints
15 limiting their efficiency. For instance, the development of electric (or hydrogen) vehicles
16 faces important technological barriers and dedicated and coordinated policies would be
17 necessary to favor their diffusion, including basic research and R&D, infrastructure
18 deployment (e.g., charging stations) and pricing incentives. For what concerns energy
19 intensity, standards (such as fuel efficiency or carbon emissions standards) help to overcome
20 private agent’s partial information and imperfect foresight when making vehicle purchase
21 decisions and have been the most effective way of reducing transportation emissions since
22 the 70’s (particularly recently with EU regulations to automakers). However, the future
23 potentials of this option may be limited by saturation of efficiency potentials in mature

1 fleets, inertias due to the political economy of tightening standards and the slow renewal of
2 vehicles' fleet (notably in developed countries).

3 Because of these obstacles, it appears necessary to consider specific measures on the
4 "behavior" determinants of transport-related emissions, namely mobility volume and
5 structure. To reduce overall demand for transportation, some degree of reorganization of
6 firms' production/distribution process and households' patterns of consumption is necessary
7 (McKinnon, 2010; Piecyk and McKinnon, 2010; Bristow et al., 2008). Both are closely
8 dependent upon the spatial organization of the economy. In fact, concentration of
9 production units as well as their location with respect to consumption areas is crucial
10 determinant of the volume and modes of freight transport necessary for production.

11 Moreover, households' mobility is strongly constrained by the necessity to access to
12 essential activities and especially to commute for work purpose. The latter is strongly
13 correlated with the spatial organization of human settlements, and especially with the
14 development patterns of urban areas (according to (UN, 2011), 77% of population in
15 industrialized world live in urban areas, whereas this percentage is about 46% in developing
16 countries and is expected to increase rapidly over the next decades). Many econometric
17 studies have demonstrated that energy consumption (and CO₂ emissions) from transport are
18 correlated with population density or other more precise city morphological indicators
19 (measuring city shape, accessibility to public transport, etc) (Mindali et al., 2004; Bento et
20 al., 2003; Grazi et al., 2008; Le Néchet, 2011). Several case studies discuss the hypothesis of
21 the compact city as a sustainable urban form (Holden and Norland, 2005; Muniz and
22 Galindo, 2005) and the association between automobile dependence (or emissions) and land
23 use planning and regulations (Newman and Kenworthy, 1996; Glaeser and Kahn, 2010).

24 Moreover, developing public transport network to favor modal shift is beneficial if the

1 density of settlements is sufficient. This means that a voluntarist reorientation of
2 investments towards public modes cannot but be associated with policies that affect
3 households and firms locations (notably land-use policies, fiscal policies to control land
4 markets etc.) (Shalizi and Lecocq, 2009).

5 Complementary policies on the demand side should thus include infrastructure policies,
6 fiscal policies, land-use policies, building regulations and other policies affecting how
7 buildings are designed, but also industrial policies and other regulations that affect how
8 firms locate. In addition to these “physical policies” (i.e. policies dealing with a physical
9 infrastructure element), “soft policies”, in particular those replacing physical mobility by
10 telecommunications, should be considered (see Cairns et al. 2004; Anable et al., 2005; Cairns
11 et al., 2008; Santos et al., 2010).

12

13 **3 - Modeling the transport-energy-economy nexus of mitigation costs**

14 The points made above are by no means new discoveries and were already evident when
15 climate emerged as a major issue in the late 80s. One could then expect that modeling
16 frameworks developed to assess the costs of climate policies would have embarked the
17 specificities of the transportation sector through joint frameworks between energy,
18 transportation and urban dimensions (Hourcade, 1993). However, the overwhelming
19 majority of energy-economy-environment (E3) models conventionally used to assess
20 mitigation costs reveals a methodological lock-in towards a focus on energy at the detriment
21 of an explicit representation of transport dynamics and adopt carbon price as the only driver
22 of decarbonizing economies (IPCC, 2007). Of course, the transportation sector is not absent
23 from these models but most of them still lack an explicit representation of the non-price

1 drivers and lifestyles (recent steps in this direction include (Anable et al., 2012) and (Brand et
2 al., 2012).

3 Schafer (2012) offers an overview of the state of the art of transportation representations in
4 E3 models, and calls for the introduction of behavioral change into these models. This means
5 bridging a gap between (i) bottom-up technology-rich models, which rely on exogenous
6 trends of transportation demands, and therefore have no endogenous evolution of modal
7 choices or mobility volumes, and (ii) top-down macroeconomic models, which
8 conventionally represent the transportation sector in nested CES (constant elasticity of
9 substitution) production functions, so that demand changes are exclusively price-induced.
10 Moreover, none of these two types of models can account for the “rebound effect”
11 following technology improvement nor for the “induced demand effect” following
12 infrastructure development.

13 We adopt the E3 model Imaclim-R (Waisman et al, 2012), which belongs to the family of
14 models trying to bridge the gap between bottom-up and top-down models and to introduce
15 to various extent non-energy and non-price drivers of transportation dynamics (see Schafer,
16 2012 for an overview).

17

18 **3.1 General architecture of the IMACLIM-R model**

19 The hybrid dynamic general equilibrium model IMACLIM-R proposes a framework that helps
20 disentangling the role of transport in long-term socio-economic trajectories and the
21 potentials offered by specific measures on this sector for mitigation costs.

22 IMACLIM-R is a model of the world economy² that covers the period 2001-2100 in yearly steps
23 through the recursive succession of annual static equilibria and dynamic modules (Figure 1).

1 The *annual static equilibrium* determines relative prices, wages, labour, value, physical flows,
2 capacity utilization, profit rates and savings at date t as a result of short term equilibrium
3 conditions between demand and supply on goods, capital and labor markets. The *dynamic*
4 *modules* are sector-specific reduced forms of technology-rich models, which take the static
5 equilibria at date t as an input, assess the reaction of technical systems to the economic
6 signals, and send new input-output coefficients back to the static model to compute the
7 equilibrium at $t+1$. Technical choices are flexible but, in a “putty-clay” representation
8 (Johansen, 1959), they modify only at the margin the input-output coefficients and labor
9 productivity embodied in the existing equipment that result from past technical choices to
10 represent the inertia in technical systems and the role of volatility in economic signals.

11 [Insert Figure 1 here]

12 The consistency of the iteration between the static equilibrium and dynamic modules relies
13 on ‘hybrid matrices’ (Hourcade et al., 2006), which ensure a description of the economy in
14 consistent money values and physical quantities (Sands et al., 2005). This dual description
15 represents the material and technical content of production processes and guarantees that
16 the projected economy is supported by a realistic technical background (informed by expert
17 views or sectoral analyses) and, conversely, that any projected technical system corresponds
18 to realistic economic flows and consistent sets of relative prices. In climate policy analysis,
19 this dual approach is crucial for energy goods to represent explicitly their carbon-to-energy
20 ratio (Malcolm and Truong, 1999). IMACLIM-R extends it to transportation as another key
21 sector of climate analysis by adopting an explicit representation of passenger and freight
22 mobility, expressed in passenger-km and ton-km respectively.

23

1 **3.2 Modeling the dynamics of the transportation sector**

2 This section enters more into the details of the representation of transport in the IMACLIM-R
3 model and sketches the way its major determinants are captured.

4 **3.2.1 Passenger mobility demand**

5 Households derive utility from the consumption of goods i above its minimum level,
6 $C_i - C_i^{(0)}$, and mobility services S_m :

$$7 \quad U = \left[\prod_{\text{goods } i} (C_i - C_i^{(0)})^{\xi_i} \right] \cdot (S_m - S_m^{(0)})^{\xi_m} \quad (1)$$
$$8 \quad \text{where } S_m = \left[\sum_{\text{modes } j} \left(\frac{pkm_j}{b_j} \right)^\eta \right]^{\frac{1}{\eta}}$$

9 Here, the aggregate mobility service S_m is defined as a CES composite of pasengers.km in the
10 four modes under consideration (air, road, public³, and non-motorized) with the elasticity of
11 substitution between modes η and mode-specific parameters b_j . The basic needs of mobility
12 $S_m^{(0)}$ measures constrained mobility (ie the minimum level that households have to satisfy,
13 essentially for commuting) and ξ_m is the elasticity of utility to the level of mobility service.

14 Households maximize utility under a twofold constraint that affects transportation decisions.
15 On the one hand, the standard budget constraint (2) captures that transport-related
16 expenditures enter into a tradeoff with the consumption of other goods C_i paid at price p_i .
17 The mobility services provided by public and air transport modes are paid at their end-use
18 prices, p_{public} and p_{air} respectively, including fuel, O&M and capital costs. On the contrary,
19 private modes are auto-produced by households at an end-use price that only includes liquid
20 fuels (or electricity) costs (paid at prices p_{liquid} and p_{elec} respectively), given aggregate unitary

1 consumption per unit of distance, α_{liquid}^{cars} and α_{elec}^{cars} . Note that fixed costs associated to car
 2 ownership do not enter into this tradeoff, but are considered in households investments.
 3 The income constraint can then be written as

$$4 \quad Income = \sum_i p_i \cdot C_i + P_{public} \cdot pkm_{public} + P_{air} \cdot pkm_{air} + (\alpha_{liquid}^{cars} \cdot P_{liquid} + \alpha_{elec}^{cars} \cdot P_{elec}) pkm_{cars} \quad (2)$$

5
 6 On the other hand, the demand for transportation services by households and modal share
 7 is constrained by a time budget constraint (3) to represent the stability of travel time budget
 8 across time and space at a regional or national scale. This assumption is supported by
 9 number of studies, which demonstrate that, at an aggregate and average level, households
 10 allocate a fixed amount of time T_{disp} to transportation, regardless of transportation costs.
 11 (see Mokhtarian and Chen (2004) for an extended discussion), with rather close outcomes in
 12 terms of travel time budgets: 1.1–1.3 h per traveler per day (Zahavi and Talvitie, 1980), 50
 13 min to 1.1 h per person per day (Bieber et al., 1994), 1.1 h per person per day (Schafer
 14 and Victor, 2000) or 1.3 h per person per day (Vilhelmson, 1999). The time constraint can
 15 then be written as:

$$16 \quad T_{disp} = \sum_{Modes\ j} \int_0^{pkm_j} \frac{du}{v_j(u)} \quad (3)$$

17
 18 In equation (3), $v_j(u)$ measures the marginal speed of transportation mode j , that is the
 19 speed for one additional passenger-kilometer. This variable depends on congestion effect, as
 20 measured by the utilization rate of transportation capacities for mode j , $Captransport_j$: the
 21 higher the utilization rate, the lower the effective “speed” of the mode (Figure 2). This

1 representation is an extrapolation, at a very aggregated level, of the “macroscopic
2 fundamental diagram” on the relations between vehicles fluxes, speed and infrastructure
3 capacity at the scale of a large transportation network (Geroliminis and Danganzo, 2008).
4 This curve is specific to each mode with, for example, very little (strong) effect for rail
5 passenger (road) transport⁴.

6 [Insert Figure 2 here]

7 This structure with a twofold constraint allows capturing number of stylized facts of
8 passenger transportation:

- 9 • the rebound effect of energy efficiency improvements on mobility: more efficient
10 transportation vehicles free up resources (*via* lower fuel expenditures), which allow
11 an increase consumption of all goods and services within budget constraint (2),
12 including higher mobility demand.
- 13 • the induction effect of infrastructure deployment on mobility demand: for a given
14 transportation mode, adding up infrastructure decreases the congestion constraint
15 but the marginal effect of infrastructure deployment depends on the shape of the
16 congestion curve (Figure 2). This makes passenger.kms in that mode less time-
17 consuming and allows households to increase overall travel demand within their time
18 budget (3).
- 19 • the modal breakdown between different modes: the four modes (air, road, public,
20 and non-motorized) are explicitly differentiated according to their costs, mobility
21 service (measured by their speed) and the availability of infrastructure determining
22 congestion levels. Given these characteristics, effective modal breakdown then
23 results endogenously from a tradeoff within the twofold income constraint (2) and

1 time budget (3). Note that the time budget constraint implies an implicit value of
2 travel time, given by the Lagrangian multiplier of the constraint in households'
3 maximization program.

- 4 • the constraints imposed on mobility needs by firms' and households' location: this
5 concerns in particular the importance of daily travels that households have no choice
6 but to realize to satisfy specific travel purposes (essentially, commuting and shopping
7 travels. They are represented by the basic needs parameter $S_m^{(0)}$ in equation (1).

8

9 **3.2.2 Freight mobility demand**

10 Production possibilities in all sectors are described using a Leontief function with fixed
11 intensity of labor, energy and other intermediary inputs in the short-term (but with a flexible
12 utilization rate of installed production capacities). This means in particular that, at a given
13 point in time, the intensity of production in each of the three freight transportation modes
14 (air, water and terrestrial transport) is measured by input-output coefficients $IC_{F,j}$, which
15 define a linear dependence of freight mobility in a given mode j to production volumes. Note
16 that "terrestrial transport" includes both trucks and rail modes because of data limitations,
17 since the two modes correspond to a single aggregated sector in the economic accounting
18 matrixes used for Imacim-R calibration, GTAP 6 (Dimaranan and McDougall, 2006). The
19 input-output coefficients capture implicitly (a) the spatial organization of the production
20 processes in terms of specialization/concentration of production units and (b) the
21 constraints imposed on distribution in terms of distance to the markets and just-in-time
22 processes, both driving the modal breakdown and the intensity of freight mobility needs.
23 The input-output coefficients evolve in time to capture changes in the energy efficiency of

1 freight vehicles, in the logistic organization of the production/distribution process and in the
2 modal breakdown.

3

4 **3.2.3 Transportation technologies and energy efficiency**

5 The motorization rate determines the access to the automobile mode among households'
6 choices. In each region, it is related to per capita disposable income with a variable income-
7 elasticity in function of income levels (Dargay et al, 2007): in regions with low income per
8 capita, the elasticity is maintained at a low level (0.3) because very poor people rely
9 essentially on non-motorized modes and public transport; at middle-income levels (from
10 \$3,000 to \$10,000 per capita), this elasticity is set at 2 to capture the acceleration of the
11 access to private motorized mobility (motorization grows twice as fast as income); finally, at
12 the highest levels of income comparable to those in the OECD, the elasticity decreases
13 progressively to represent equipment saturation and it is assumed, in particular, that the
14 motorization rate never exceeds the current US value (0.7 vehicle per person)

15 Energy efficiency in private vehicles is measured by the evolution of parameters α_{liquid}^{cars} and
16 α_{elec}^{cars} in equation (2), which result from households' decisions on the purchase of new
17 vehicles among three types of technologies: standard vehicles (consuming only liquids),
18 hybrid cars (consuming both electricity and fuels) and "electric vehicles" (using only
19 electricity). The description of transport technologies remains at a rather aggregate level to
20 facilitate the dialogue with the top-down macroeconomic description: "electric vehicles"
21 represent implicitly all types of vehicles that use electricity as service provider, including fuel
22 cells and hydrogen vehicles. Technologies are differentiated by their unitary fuel
23 consumption and their capital costs (endogenously decreasing in function of the learning-by-

1 doing process), and decisions among them are based on a mean cost minimization criterion
2 under imperfect expectations.
3 Energy efficiency for freight transportation is not represented through explicit vehicle
4 technologies but is captured implicitly through the evolution of the input-output coefficients
5 measuring, for each mode (water, air and terrestrial transport), the energy requirements for
6 the production of final transportation goods. These coefficients are responsive to energy
7 price variations to capture the incentive for technical progress in function of market
8 conditions (for example, the average fuel consumption of trucks evolves with a (-0.3) price-
9 elasticity).

10 **4 –Low carbon society and the transportation sector**

11 **4.1 Definition of the scenarios**

12 To quantitatively assess the role of targeted policies for the transportation sector in the
13 transformation to low carbon societies, two sets of scenarios are compared. Both
14 correspond to the same climate objective, as captured by an identical emission trajectory
15 corresponding to a stabilization target of 440–485 ppm CO₂: global CO₂ emissions peak in
16 2017 and are decreased by 20% and 60% with respect of 2000 level in 2050 and 2100,
17 respectively (Barker et al. 2007, Table TS2). Each year, the model finds the level of carbon tax
18 that constrains emissions to the exogenous target given for that period, tax revenues are
19 recycled in a lump-sum manner within each region⁵.

20 The two sets of scenarios are distinguished by the nature of transport-related policies that
21 are introduced in parallel with the carbon tax.

1 In the first set of scenarios (S1), a continuation of current trends in terms of investment
2 choices driving mobility demand is assumed:

- 3 • Constrained mobility (measured by $S_m^{(0)}$ in equation (1)) evolves proportionally to
4 total mobility S_m . This assumption is consistent with the constancy of the ratio of
5 Commuting Distances over Total mobility (around 30%) in the United States over the
6 period 1969-2009 (NHTS, 2009). For the sake of simplicity, this assumption is
7 extended to all regions and this share is taken equal to 50% to account for all basic
8 mobility purposes (including commuting but also shopping, access to services). This
9 represents a proxy for a continuation of urban sprawl when households gain better
10 accessibility thanks to increased performance of transport modes.
- 11 • The allocation of investments in transportation infrastructure follows mobility
12 demand for each transportation mode. This means that investments are decided so
13 that the extensions of the infrastructure network associated to a given mode (roads,
14 railways, airports) follow the increase of passenger-km covered with this mode. This
15 is a proxy to represent that investment choices are mainly driven by the objective to
16 avoid congestion.
- 17 • The freight transport intensity of production remains constant ie the input coefficient
18 per unit of production remains at its baseline level. This means that the
19 production/distribution process keeps a similar organization throughout the period
20 and responds to transport cost increases (either due to energy or carbon prices) by
21 maintaining a constant dependence on transport instead of the increase observed in
22 recent years (McKinnon et al., 2010).

1 In the second set of run (S2), specific measures are implemented to control the "behavior"
2 determinants of transportation in the course of the low-carbon transition. At this scale of
3 analysis, only very stylized representations are possible, they are "proxies" to encapsulate
4 rich policy packages implemented at different spatial scales; a detailed description of the
5 content of these policies can be found in (Santos et al., 2010) for passengers mobility and
6 (McKinnon et al., 2010) for freight transportation (the articles cited in the first paragraph of
7 section 2.2 also provide case studies of such policy packages).

8 We test here the effect of these measures at an aggregate level if they are able to trigger (i)
9 spatial reorganizations at the urban level and soft measures towards less mobility-
10 dependent agglomerations, (ii) reallocation of investments in favor of public modes at
11 constant total amount for transportation infrastructure and (iii) adjustments of the logistics
12 organization to decrease the transport intensity of production/distribution processes and
13 optimize the use of vehicles (e.g., through improved backloading, more space efficient
14 packaging, more transport-efficient order cycles, etc.) in anticipation of very high long-term
15 transport costs. These measures affect three crucial determinants of transport activities that
16 are explicitly represented in IMACLIM: basic mobility $S_m^{(0)}$ (equation (1)), transport capacities
17 $Captransport_j$ (equation (3)) and $IC_{F,j}$ (section 2.2.2).

18 Given the absence of reliable and comprehensive data on the cost of implementation of
19 these measures, a redirection of investments at constant total amount is assumed and the
20 following simplifying assumptions are made:

- 21 • a progressive decoupling of basic mobility $S_m^{(0)}$ with respect to total mobility S_m from
22 50% in 2020 to 40% in 2060 and after.

- 1 • a limitation of investments in road and air infrastructures causing a saturation of
2 transportation capacities $Captransport_{road}$ and $Captransport_{air}$ and hence a maximum
3 threshold to mobility offered by these modes targeted at 7500km/capita and
4 2000km/capita respectively. These levels correspond approximately to current
5 mobility levels in Europe for road transport, and in North America for air transport.
6 Note that for regions (essentially North America) with mobility levels above the
7 threshold for road transport, a stagnation of transportation capacities are assumed.
- 8 • a 1% yearly decrease of $IC_{F,j}$ representing a decrease of the transport intensity of
9 production/distribution processes, and a 50% increase of the terrestrial freight
10 transportation energy efficiency reactivity to energy prices, representing the
11 optimization of vehicles use.

12

13 The modeling experiment then comprises:

- 14 - 48 BAU scenarios, corresponding to scenarios for which there is no constraint on CO2
15 emissions.
- 16 - 48 S1 stabilization scenarios, corresponding to stabilization scenarios with a “carbon
17 price only” strategy.
- 18 - 48 S2 stabilization scenarios, where “transportation policies” are implemented as
19 complementary measures to the carbon price.

20 These scenarios delineate the uncertainty on (i) Oil and Gas supply, (ii) coal supply, (iii)
21 substitutes to oil, (iv) technological change and technologies potentials and costs, (v)
22 lifestyles evolutions (see more details in (Waisman et al., 2012)). Here, we focus on the
23 transportation sector, and its interactions with the rest of the economy, to disentangle the

1 mechanisms at play in the alternative dynamics of passengers' transportation (Section 4.2)
2 and freight transportation (Section 4.3), and analyze how the impacts of these alternative
3 dynamics impact the rest of the economy (Section 4.4).

4 **4.2 Climate policy and Passenger transport**

5 Even in stabilization scenarios, the emissions from passengers' transport are increasing
6 during the first half of 21st century and remain above their 2010 level in 2100 for all
7 scenarios (Table 1). This means that, in stabilization scenarios where global emissions are
8 decreased by 60% compared to 2000, transport represents a dominant share of remaining
9 emissions at the end of the century (up to 70% in S1). Average emissions from passenger
10 transport are close in the two stabilization scenarios (4.8 GtCO₂), but the upper bounds are
11 significantly higher in S1. This demonstrates the risk of high passenger transport emissions in
12 absence of complementary transport-specific measures if technology potential (especially on
13 electric vehicles) are limited.

14 [Insert Table 1 here]

15 To understand the dynamics of these emissions among the modes, the mechanisms are
16 decomposed into (i) global mobility evolution, (ii) modal structure evolution and (iii) vehicle
17 fleet efficiency improvement and/or electrification.

18 (i) The rapid increase of mobility in baseline scenarios is only moderately affected by
19 mitigation policies and, in S1 and S2 scenarios, global mobility in 2100 is only 13% and 19%
20 lower than in the baseline, respectively (Table 2). This weak effect is due to the lowering of
21 international oil prices (thanks to lower oil demand induced by the climate policy) limiting
22 the increase of fuel costs and to inertia in the transportation infrastructure, which become
23 active only in the second half of the century.

1 [Insert Table 2 here]

2

3 (ii) The modal structure is similar in the baseline case and in S1 scenarios, but very different
4 in the S2 scenarios with significant shift from personal vehicles to low carbon modes (public
5 transport and non-motorized) and a moderation of air transportation increase (Table 3)

6 [Insert Table 3 here]

7 (iii) Mean liquid fuel consumption of the personal vehicle fleet captures both the increased
8 efficiency of internal combustion engines (ICE) and the electrification of the fleet through
9 the diffusion of hybrid and electric vehicles (Figure 3). In S1 scenarios, the carbon price
10 ensures significantly better vehicle efficiency than in BAU scenarios (- 28% on average in
11 2100). This efficiency effect is slowed in S2 scenarios because carbon prices are lower and
12 the fleet turn-over is slower due to lower vehicle use, both effects affecting the diffusion of
13 efficient ICE and electrified vehicles.

14 [Insert Figure 3 here]

15 This analysis demonstrates very different determinants of emission reduction trends in the
16 transportation sector depending on the measures adopted. Under “carbon-price only” (S1
17 scenarios), the major effect is due the diffusion of energy efficiency in vehicles, whereas
18 modal shift and mobility reduction play a dominant role when appropriate transport policies
19 are implemented (S2 scenarios).

20

1 **4.3 Climate policy and Freight transportation**

2 Total emissions from freight transport are on average 24% and 48% lower than in the
3 baseline for S1 and S2 scenarios respectively, the difference being critically explained by the
4 freight transportation input per unit of production in S2 and S1

5 Under carbon price only policy (S1 scenarios), the reduction of emissions from inland freight
6 due to carbon pricing is slow and moderate even on the long-run (emissions are reduced by
7 25% in 2100) (Table 4).

8 [Insert Table 4 here]

9 Under constant freight transportation input per unit of production, freight transport
10 emissions reductions come from (i) a reduction of industrial production due to contraction of
11 activity and structural change towards less transport-intensive activities (e.g., services)
12 (Figure 4) and (ii) vehicle efficiency gains allowing a decoupling of transport activity and
13 emissions (Figure 5). In S2 scenarios, the “transportation policies” contribute additionally to
14 emission reduction by decreasing the freight transportation input per unit of production and
15 the unitary liquid fuels consumption from freight transportation vehicles.

16 [Insert Figure 4 here]

17 [Insert Figure 5 here]

18 Note that maritime and air freight transport emissions are only moderately affected by the
19 climate policy. In 2100, the 23% reduction with respect to BAU is essentially due to lower
20 freight mobility needs (20% ton.kilometers on average in 2100) in parallel with less overall
21 economic activity and less trade (because of higher international transport prices implied by
22 the carbon price).

1

2 **4.4 The transportation sector in low carbon transitions: macroeconomic implications**

3 This final section analyzes how the implementation of specific measures to control mobility
4 affects the rest of the economy in the transition to low-carbon futures. Note that we limit
5 our analysis to macroeconomic assessments in GDP terms, without taking into account the
6 costs and benefits of mitigation in the form of (avoided) climate damages and adaptation
7 costs.

8 First, the carbon intensity of liquid fuels is slightly lower in S2 scenarios. Indeed, the volume
9 of biofuels is very close in the two scenarios (because it is more driven by land competition
10 than by energy prices) and lower liquid fuel production in S2 scenarios means a higher share
11 of biofuels (34.9% on average in 2100 in S2 scenarios vs. 32.4% in S1 scenarios)

12 [Insert Table 5 here]

13 Second, the sectoral structure of emission reductions is significantly different under the two
14 groups of scenarios (Table 5). The decarbonization efforts bear mainly on non-transport
15 sectors (electricity, industry and residential) since transportation has the lowest
16 decarbonisation rate (its emissions even continue to rise despite stabilization policies over
17 2010-2050 before slightly declining in the end of the period). The “transportation policies” in
18 S2 allow increasing the contribution of the transportation sector to mitigation efforts (as
19 captured by lower values of emission variations for transport in Table 5) and other sectors
20 can then slow their decarbonization effort. This concerns essentially the power sector and, in
21 the long run, the industry.

1 As a consequence, the carbon price path necessary to respect the global emissions trajectory
2 objective is lower in S2 than in S1 (Figure 6), driving reductions of macroeconomic mitigation
3 costs.

4 [Insert Figure 6 here]

5 In S1, very high carbon price are necessary in the second part of the 21st century to reach the
6 450 ppm target via the proposed emission trajectory: in 2100, the average price across
7 scenarios reach almost 600 \$/tCO₂ with a risk of attaining 1200\$/tCO₂ under the most
8 pessimistic technological assumptions. Waisman et al. (2012) showed that this high carbon
9 price is associated with high macroeconomic losses reaching on average 4.6% of BAU GDP in
10 2100. The important long-term macroeconomic losses can be explained by (i) the inertia of
11 infrastructures, location choices, and urban forms embedded in the model, and (ii) by the
12 important rebound effect of mobility that requires very high carbon prices in the second half
13 of the century to meet stringent emissions targets. In other words, lack of change in
14 infrastructure and associated demand dominate the cost assessment in the long-run, since
15 all the sectors other than transportation have already made substantive cuts in their
16 emissions.

17 In S2, the higher decarbonization of the transportation sector allows carbon prices to be
18 lower: on average carbon prices are 40% lower in 2100 in S2 scenarios than in S1 scenarios
19 and in particular, prices above 600\$/tCO₂ at this time horizon are excluded. The associated
20 macroeconomic cost of stabilization is also significantly reduced: the long-term
21 macroeconomic cost of mitigation (GDP loss compared to baseline GDP) is 0.7% in S2
22 scenarios (to be compared with 4.6% on average in S1 scenarios); in 2100 global real GDP is

1 4.2% higher on average (ranging from 1.8% to 6.7% depending on the assumptions on fossil
2 fuels supply, technologies and lifestyles) in S2 scenarios than in S1 scenarios.

3

4 **5. Conclusion**

5 This paper investigates the role (passenger and freight) transportation activities in the
6 transition to low carbon societies with a particular attention to specific measures designed
7 to control the growth of mobility. This is done by adopting a Energy-Economy-Environment
8 model that represents explicitly the transport sector, including its non-price determinants
9 (urban organization, infrastructures, spatial organization), and captures its interactions with
10 the rest of the economy through a general equilibrium setting

11 Transport proves to be the sector for which carbon emissions are the more difficult to
12 reduce and hence represents a dominant share of remaining emissions in the long-term.
13 Because of its weak reactivity to energy price increases, very high levels of carbon price must
14 be imposed in the second half of the century to reach low mitigation targets: in 2100, the
15 average value of carbon prices is around 600\$/tCO₂, with a risk of attaining 1200\$/tCO₂.

16 Controlling the growth of mobility would allow limiting these effects by offering mitigation
17 potentials independent of carbon prices. This study considers three potential sources of
18 mobility moderation: urban reorganizations lowering constrained mobility (i.e. mobility for
19 commuting and shopping), infrastructure deployment favoring low-carbon modes and
20 changes of logistics organization driving lower freight mobility intensity of
21 production/distribution. They allow excluding carbon prices above 600\$/tCO₂ and hence
22 help limiting macroeconomic cost of mitigation policies.

1 An important caveat for these conclusions is that they rely on an aggregated level of
2 description, which does not permit to represent explicitly the underlying policy measures
3 adopted at different scales to trigger these evolutions, like land planning, transport policies
4 per se or fiscal policies (e.g., Nivola, 1999). This means that we do not enter into the
5 discussions about the policy instruments to be combined, although this discussion is
6 particularly crucial for the transport sector, since the wide range of factors driving mobility
7 calls for fine adjustments of different policies. This means also that we ignore some
8 potentially important indirect effects of these policies beyond the transport sector, like
9 those affecting real estate markets, which may drive land price changes with a potentially
10 important effect on households' purchase power and location decisions.

11 Despite these limitations, our results are robust enough to conclude that investigating
12 further the synergies between carbon price schemes and a wide set of spatial and housing
13 policies aimed at controlling mobility needs is a critical precondition to set in place efficient
14 energy policies, all the more so in case of ambitious climate mitigation strategies. Further
15 investigation of these questions—and with associated issues such as welfare and distribution
16 impacts— goes along with further development of the modeling approach to embark some
17 crucial effects, like the interplay between transport infrastructure, modal choice, real estate
18 markets and scarcity rents.

19
20
21

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27 Endnotes

28 1. Recent programs have estimated the contribution of these behavioral changes
29 (International Transport Forum, 2007) and estimate that they can contribute to a 10%
30 reduction of fuel demand (Barkenbus, 2010)

31 2. The IMACLIM-R model used in this paper divides the economy in 12 regions—USA,
32 Canada, Europe, OECD Pacific, Former Soviet Union, China, India, Brazil, Middle East, Africa,
33 Rest of Asia, Rest of Latin America—, and 12 productive sectors—Coal, Crude Oil, Natural
34 Gas, Refined products, Electricity, Construction, Agriculture and related industries, Energy-
35 intensive Industries, Air Transport, Sea Transport, Other Transports, Other industries and
36 Services. In addition IMACLIM-R includes transportation with personal vehicles and non-
37 motorized transport.

38 3. The model does not differentiate between inter- and intra-city trips, so “public transport”
39 includes both urban public transports (buses, metros, etc.) and inter-city trains.

40 4. The functional form chosen for the relation between the marginal speed (v_j) in mode j and
41 the utilization of the transportation infrastructure capacity $\left(\frac{pkm_j}{Captransport_j} \right)$ is

1 $v_j(x) = \frac{v_0}{a \cdot x^\alpha + 1}$. Parameters values are calibrated such that (i) v_0 equals 700, 80 and 50
2 km/h for air transportation, cars and public transport respectively, (ii) $v_j(1) = v_1$, with v_1
3 equals 5 km/h for all modes, (iii) the households maximization program results in observed
4 data on mobility and budget shares per mode for the calibration year 2001.
5
6 5. This simplified representation of climate policies means that we ignore some dimensions
7 that may affect the cost of climate policies: the intertemporal flexibility for allocating
8 emission reductions (“when flexibility”), international redistribution of carbon tax revenues
9 or internal recycling towards a reduction of labor taxes. See IPCC (2007) for an overview on
10 these questions.
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13 List of Tables

15 Table 1: *CO₂ emissions (in GtCO₂) from passengers transport in 2010, 2050 and 2100 in BAU,*
16 *S1 and S2 scenarios. Average values across scenarios are in bold, lower and upper bounds are*
17 *into brackets. Low carbon modes include public transport and non-motorized modes.*

		2010	2050	2100
personal vehicles	BAU	3.2	4.4 [3.0 - 5.3]	4.1 [1.6 - 7.3]
	S1		4.2 [3.0 - 4.9]	2.3 [1.3 - 3.4]
	S2		3.8 [3.3 - 4.3]	2.8 [1.4 - 3.6]
low carbon modes	BAU	0.5	0.6 [0.5 - 0.7]	0.6 [0.5 - 0.6]
	S1		0.5 [0.5 - 0.6]	0.4 [0.4 - 0.5]
	S2		0.5 [0.5 - 0.6]	0.5 [0.4 - 0.5]
air transport	BAU	0.7	1.2 [0.8 - 1.4]	2.8 [2.2 - 3.4]
	S1		1.1 [0.8 - 1.3]	2.1 [1.5 - 2.5]
	S2		1.1 [1.0 - 1.2]	1.5 [1.4 - 1.7]
total passenger transport	BAU	4.4	6.2 [4.3 - 7.4]	7.5 [4.3 - 11]
	S1		5.8 [4.3 - 6.8]	4.8 [3.2 - 6.4]
	S2		5.4 [4.8 - 6.1]	4.8 [3.2 - 5.8]

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20 Table 2: *Global mobility, in passenger.kilometers per capita in 2010, 2050 and 2100 in BAU,*
21 *S1 and S2 scenarios (average values across scenarios are in bold and full range into brackets).*

	2010	2050	2100
BAU	6315	11950 [8896 - 13961]	22668 [18865 - 27267]
S1		11328 [8794 - 13406]	19608 [15968 - 24166]
S2		11294 [9480 - 12787]	18373 [15901 - 21429]

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Table 3: *Transportation modes shares in global mobility in BAU scenarios, S1 stabilization scenarios and S2 stabilization scenarios (average values across scenarios sets), in 2010, 2050 and 2100. Low carbon modes include public transport and non-motorized modes.*

	2010	2050			2100		
		BAU	S1	S2	BAU	S1	S2
Personal vehicles	49%	41%	42%	36%	33%	34%	28%
Low carbon modes	38%	39%	39%	44%	27%	28%	39%
Air transport	12%	20%	19%	20%	40%	38%	33%

6 Table 4: *CO₂ emissions (in Gt CO₂) from passengers transport in 2010, 2050 and 2100 in BAU, S1 and S2 scenarios. Average values across scenarios are in bold, lower and upper bounds are into brackets.*

		2010	2050		2100	
			BAU	[]	BAU	[]
inland freight	BAU	1.8	1.8	[1.5 - 2.1]	2.0	[1.6 - 2.5]
	S1		1.7	[1.4 - 1.9]	1.5	[1.4 - 1.7]
	S2		1.4	[1.1 - 1.6]	0.9	[0.8 - 1.0]
other freight	BAU	0.5	0.5	[0.4 - 0.6]	0.5	[0.4 - 0.7]
	S1		0.5	[0.4 - 0.5]	0.4	[0.3 - 0.5]
	S2		0.5	[0.4 - 0.5]	0.4	[0.4 - 0.5]
total freight transport	BAU	2.3	2.3	[1.9 - 2.7]	2.5	[2 - 3.2]
	S1		2.2	[1.8 - 2.4]	1.9	[1.7 - 2.2]
	S2		1.9	[1.5 - 2.1]	1.3	[1.2 - 1.5]

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10 Table 5: *Mean annual emissions reductions (negative numbers) or increases (positive numbers), in %, over 2010-2050 and 2050-2100 in S1 and in S2 scenarios. Average values across scenarios are in bold, lower and upper bounds are into brackets.*

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		2010-2050		2050-2100	
		BAU	[]	BAU	[]
Transports	S1	0.4	[0.1 - 0.7]	-0.3	[-0.6 - -0.1]
	S2	0.2	[0.0 - 0.5]	-0.4	[-0.7 - -0.1]
Electricity	S1	-3.7	[-5.1 - -2.6]	-4.6	[-6.0 - -3.5]
	S2	-3.4	[-4.5 - -2.6]	-4.0	[-5.5 - -2.0]
Industry	S1	-1.3	[-1.6 - -1.0]	-3.7	[-4.5 - -2.8]
	S2	-1.2	[-1.4 - -0.9]	-3.0	[-3.8 - -2.3]
Residential	S1	-0.5	[-0.7 - -0.3]	-0.8	[-1.0 - -0.5]
	S2	-0.4	[-0.6 - -0.2]	-0.8	[-1.0 - -0.4]
Other sectors	S1	-1.7	[-2.4 - -0.8]	-2.9	[-3.4 - -1.8]
	S2	-1.7	[-2.4 - -1.3]	-2.4	[-2.9 - -1.2]

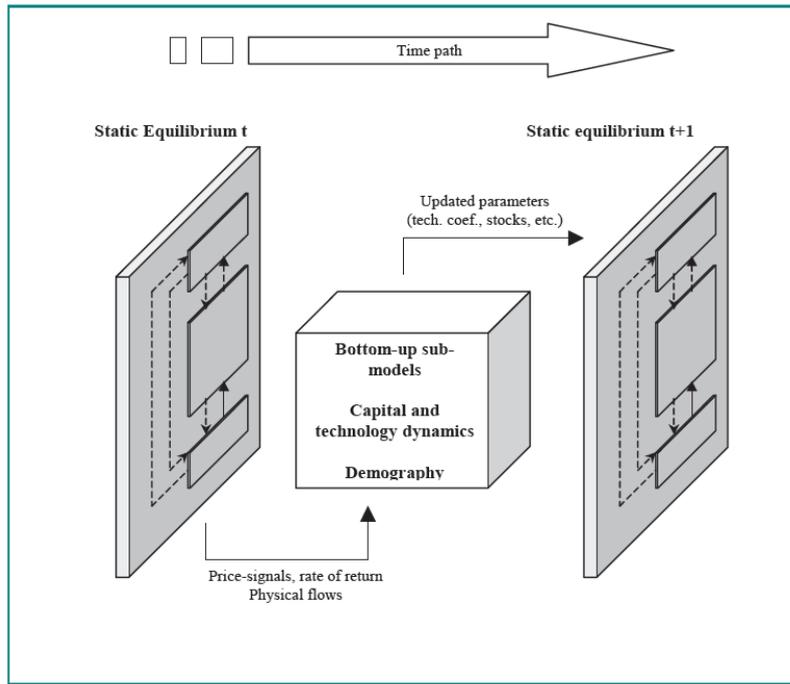
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17 **List of Figures**

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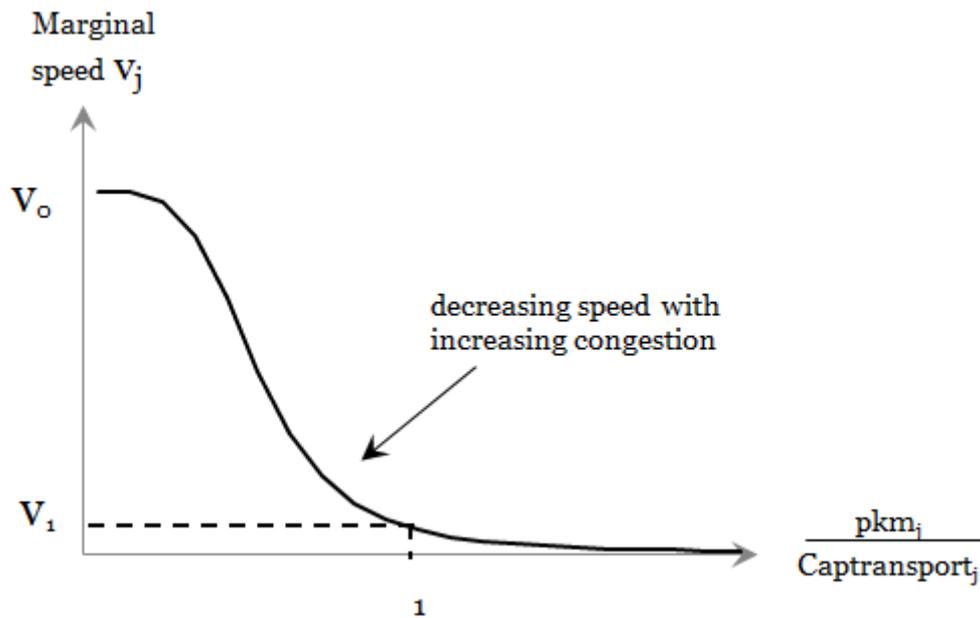
1 Figure 1. Recursive and modular architecture of the IMACLIM-R



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3 Figure 2. Marginal time efficiency of transportation mode j

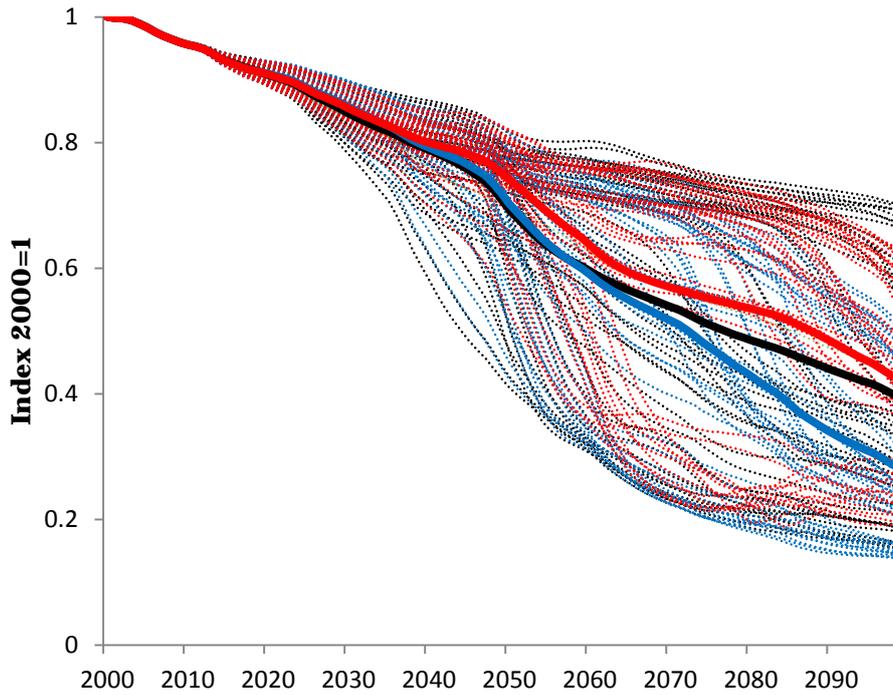
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6 Figure 3: Mean liquid fuel consumption of the personal vehicle fleet over 2000-2100 in BAU
 7 (black), in S1 (blue) and S2 (red) scenarios, as an index of 2000 level. Average values are in
 8 bold lines.

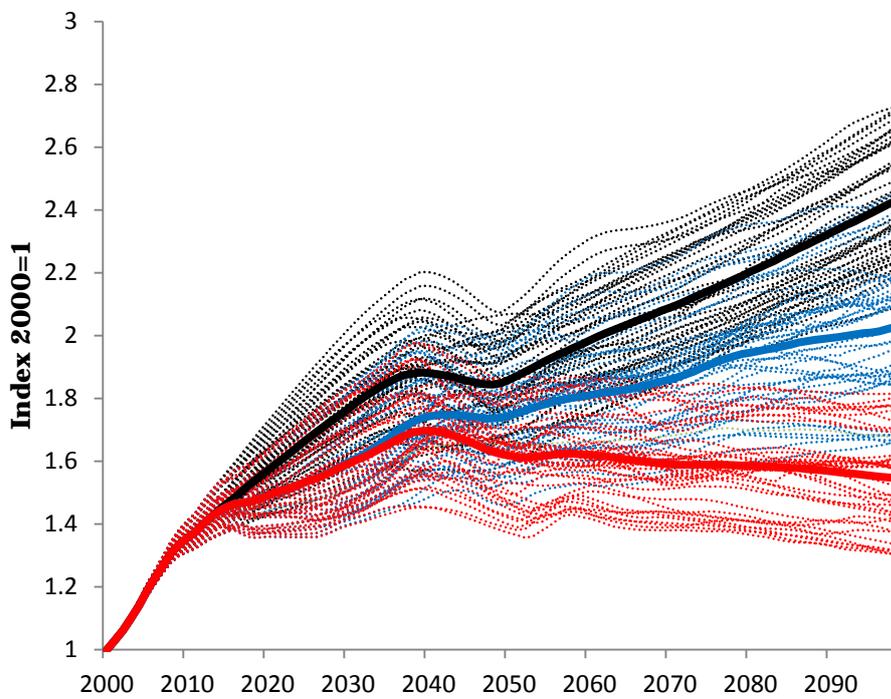
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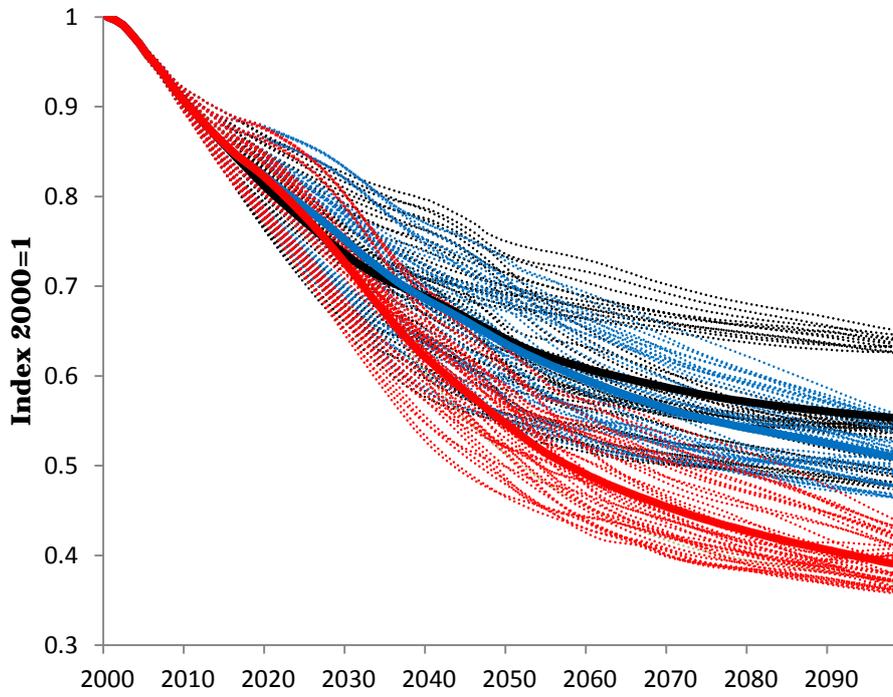
2 Figure 4: Global inland freight transportation activity index (ton.kilometers) over 2000-2100
 3 in BAU (black), in S1 (blue) and S2 (red) scenarios. Average values are in bold lines.

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1 Figure 5: *Inland freight transportation liquid fuel consumption per ton.kilometer over 2000-*
2 *2100 in BAU (black), in S1 (blue) and S2 (red) scenarios, as an index of 2000 level. Average*
3 *values are in bold lines.*
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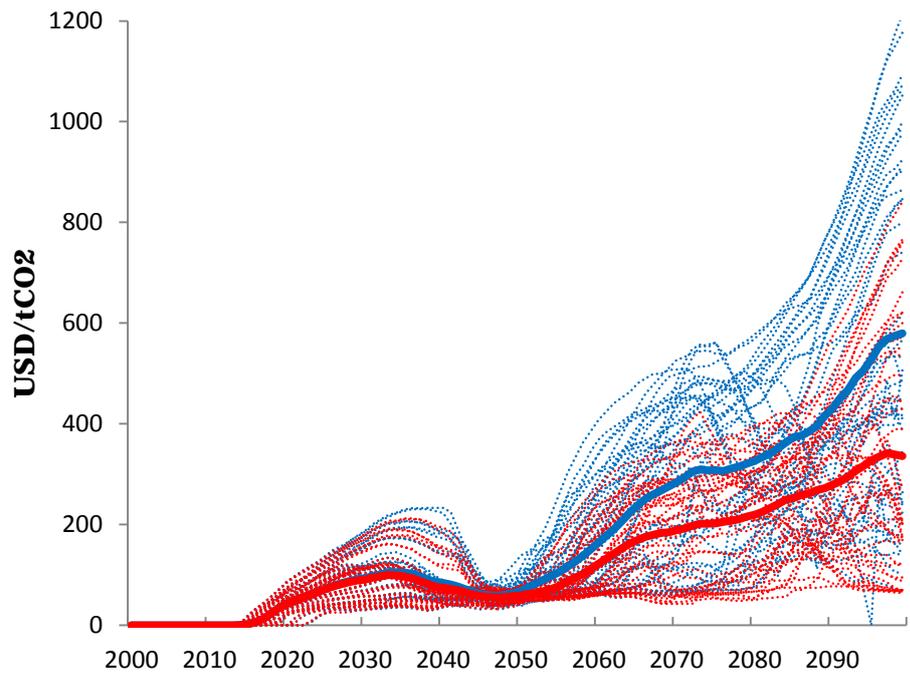
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10 Figure 6: *Price path of carbon (in [constant 2010] U.S. dollars/tCO₂) in S1 (blue) and in S2 (red)*
11 *scenarios. Average values in bold lines.*

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