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

Abstract

There is still a controversy as to the effect of spatial organization on CO_2 emissions. This paper contributes to this debate by investigating the potentials offered by infrastructure measures favoring lower mobility in the transition to a low-carbon economy. This is done by embarking a detailed description of passenger and freight transportation in an energy-economy-environment (E3) model. In addition to the standard representation of transport technologies, this framework considers explicitly the “behavioural” determinants of mobility that drive the demand for transport but are often disregarded in mitigation assessments: constrained mobility needs (essentially commuting) imposed by the spatial organization of residence and production, modal choices triggered by installed infrastructure and the freight transport intensity of production processes. This study demonstrates that the implementation of measures fostering a modal shift towards low-carbon modes and a decoupling of mobility needs from economic activity significantly modifies the sectoral distribution of mitigation efforts and reduces the carbon tax levels necessary to reach a given climate target relatively to a “carbon price only” policy. This result is robust to a wide range of assumptions about exogenous parameters.

Keywords: transport, mitigation policy, infrastructure, spatial organisation

JEL: C68, O18, R40

1 - Introduction

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

A large body of literature explores mitigation options and policies in the transport sector and emphasizes that ambitious reductions in the transport sector would require actions on both the “technology” side to decrease both the energy intensity of transportation modes and the carbon content of fuels, and on the “behaviour” side to reduce the volume of mobility and foster the adoption of low-carbon modes. This diagnosis contrasts with existing analyses of the transport sector with energy-economy-environment (E3) models, which are useful tools to investigate the role of transportation in the transition to a low-carbon economy, given the important interactions between transportation and the rest of the economy. However, these approaches remain limited to explore the full mitigation potentials of the transport sector because they have essentially focused on the assessment of the “technology” side (e.g. Schafer et al., 2009). To provide a more comprehensive vision, these tools have to be complemented with representation of the “behavioural” determinants of transportation dynamics (Schafer, 2012).

This paper is an attempt to bridge the gap between studies of mitigation options and policies in the transport sector and E3 models. It first reviews the literature on climate policies and the transportation sector, to delineate the determinants and obstacles to CO_2 emissions reduction in that sector (section 2.1) and emphasize the potential role of policies on the “behaviour” side of transportation dynamics (section 2.2). Section 3 describes how stylized representations of the “behavioural” determinants are introduced in the E3 model Imaclim-R (Waisman et al., 2012) to explicitly represent the interplay between transportation, energy and growth patterns when accounting for the rebound effect of energy efficiency improvements on mobility, endogenous mode choices in relation with infrastructure availability, the impact of investments in infrastructure capacity on the amount of travel, and the constraints imposed on mobility needs by firms’ and households’ location. This framework is then used in Section 4 to assess the role of transportation in low-carbon pathways.

This analysis demonstrates the risk of high losses if using carbon price as the sole instrument, and investigates the potentials offered by richer combination of measures. Complementarily to carbon pricing, this study considers more specifically actions to control the ”behavior” determinants of transportation in the course of the low-carbon transition, including (i) spatial reorganizations at the urban level and soft measures towards less mobility-dependent agglomerations, (ii) reallocation of investments in favor of public modes at constant total amount for transportation infrastructure and (iii) adjustments of the logistics organization to decrease the transport intensity of production/distribution processes and optimize the use of vehicles. This analysis provides a first step towards the identification of non-energy determinants of global mitigation costs and concludes with a roadmap for further integrating transportation, housing and urban dynamics issues into macroeconomic assessment of climate policies.

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2 - Climate policies and the transportation sector

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

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

Technology

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

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

The *energy intensity of mobility* results from the technical characteristics of the vehicle fleet for which improvements may be limited by asymptotes on technical progress of drive train efficiency and inertias on the deployment of new energy-efficient vehicles. Indeed, the market potential may be only a fraction of its economic potential if, under partial information and imperfect foresight about the future of energy costs (Allcott, 2010; Anderson et al, 2011; Allcott, 2011), purchase decisions under-value or even ignore future energy savings of vehicle efficiency (Greene, 1998; Turrentine and Kurani, 2007) and are importantly influenced by other considerations than energy consumption (e.g., safety, performance, size). Standards have proven efficient to foster the diffusion of more carbon efficient vehicles (around 140gCO2/km), but their effect at more stringent constraints may be limited in absence of clear price-signals allowing an appraisal of long-term benefits in terms of energy savings.

Behaviour

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

The *volume of mobility* results from households' tradeoffs between passenger transport and the demand for other goods under budget and time constraints, as well as firms' freight mobility needs in the production/distribution process. These decisions are constrained by the interplay between four effects, each of them imposing inertia on the dynamics of mobility. First, passenger daily commuting distances and the transport intensity of production are defined by the spatial distribution of housing, transport and industrial infrastructures, which are long-lived and hence characterized by strong inertias. Second, location choices, and hence mobility needs, are decided in function of a tradeoff between transport and housing expenditures. The decrease of transport prices in real terms (ie with respect to income) combined with an increase of housing prices are at the root of urban sprawl triggering a rise of mobility needs (Brueckner, 2000). These trends could be reversed only if the dynamics of transport and housing sectors are reversed. Third, in line with the seminal work by (Zahavi and Talvitie, 1980) confirmed by more recent studies (Metz, 2008; Schäfer et al, 2009; Schäfer, 2012), households are conventionally assumed to devote a given time to mobility so that speed gains permitted by infrastructure deployment may give rise to increased distances (longer daily travels and more occasional trips) and modal shifts (in favor of fast modes within the time constraint, like aviation). Finally, the tradeoff between inventories and just-in-time organizations decides the logistics organization and in particular the total vehicle-kilometers travelled for the production/distribution of a given volume of goods (McKinnon, 2010; Piecyk and McKinnon, 2010).

Moreover, two well-known feedback effects apply to the volume of mobility (Hymel et al., 2010). On the one hand, the “induced demand effect” (Goodwin, 1996) is a response to infrastructure building or improvement, which may trigger an increase of mobility because of enhanced accessibility or improved services provided by a given mode. In the long run, enhanced accessibility also changes the economic value of land, affecting the locations of activities and housing and hence mobility needs (Noland, 2008). The influence of the “induced demand effect” on CO_2 emissions is described in Shalizi and Lecocq (2009) for the case of the US Interstate Highway. On the other hand, the “rebound effect” captures the increase of mobility consecutive to reductions of the marginal costs of travel permitted by fuel economy under improved efficiency (Greening et al, 2000). The magnitude of this effect can be very significant: for instance, Wang et al. (2012) estimate that the average rebound effect for passenger transport by urban households is around 96%, indicating that the majority of expected reduction in energy consumption (and CO_2 emissions) from efficiency improvement could be offset.

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

2.2 Mitigation policies in the transport sector

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

Besides the issue of the relative importance of actions on the "technology" side vs. actions on the "behavior" side, the question of the policy instruments to trigger emissions reductions is central.

2.2.1 Price signals, energy demand and carbon emissions

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

This review demonstrates that only a sustained increase of price signals in the very long run is likely to affect significantly transport-related carbon emissions. However, only high carbon prices would trigger a notable increase of fuels' end-use price. For instance a price of carbon of 40-100 $\$/CO_2$—in the very high range of what is currently considered feasible at large scale—would translate in a moderate 0.35–0.90 $ per gallon increase in gasoline cost. Looking forward, the IPCC thus estimate that multiplying the price of carbon by 5 in 2030 (from 20$/t$CO_2$ to 100$/t$CO_2$) would only induce a 23% decrease of transport-related carbon emissions (IPCC, 2007).

2.2.2 The role of mobility-control measures

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

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

Because of these obstacles, it appears necessary to consider specific measures on the "behavior" determinants of transport-related emissions, namely mobility volume and structure. To reduce overall demand for transportation, some degree of reorganization of firms' production/distribution process and households' patterns of consumption is necessary (McKinnon, 2010; Piecyk and McKinnon, 2010; Bristow et al., 2008). Both are closely dependent upon the spatial organization of the economy. In fact, concentration of production units as well as their location with respect to consumption areas is crucial determinant of the volume and modes of freight transport necessary for production. Moreover, households' mobility is strongly constrained by the necessity to access to essential activities and especially to commute for work purpose. The latter is strongly correlated with the spatial organization of human settlements, and especially with the development patterns of urban areas (according to (UN, 2011), 77% of population in industrialized world live in urban areas, whereas this percentage is about 46% in developing countries and is expected to increase rapidly over the next decades). Many econometric studies have demonstrated that energy consumption (and CO_2 emissions) from transport are correlated with population density or other more precise city morphological indicators (measuring city shape, accessibility to public transport, etc) (Mindali et al., 2004; Bento et al., 2003; Grazi et al., 2008; Le Néchet, 2011). Several case studies discuss the hypothesis of the compact city as a sustainable urban form (Holden and Norland, 2005; Muniz and Galindo, 2005) and the association between automobile dependence (or emissions) and land use planning and regulations (Newman and Kenworthy, 1996; Glaeser and Kahn, 2010). Moreover, developing public transport network to favor modal shift is beneficial if the density of settlements is sufficient. This means that a voluntarist reorientation of investments towards public modes cannot but be associated with policies that affect households and firms locations (notably land-use policies, fiscal policies to control land markets etc.) (Shalizi and Lecocq, 2009).

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

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

The points made above are by no means new discoveries and were already evident when climate emerged as a major issue in the late 80s. One could then expect that modeling frameworks developed to assess the costs of climate policies would have embarked the specificities of the transportation sector through joint frameworks between energy, transportation and urban dimensions (Hourcade, 1993). However, the overwhelming majority of energy-economy-environment (E3) models conventionally used to assess mitigation costs reveals a methodological lock-in towards a focus on energy at the detriment of an explicit representation of transport dynamics and adopt carbon price as the only driver of decarbonizing economies (IPCC, 2007). Of course, the transportation sector is not absent from these models but most of them still lack an explicit representation of the non-price drivers and lifestyles (recent steps in this direction include (Anable et al., 2012) and (Brand et al., 2012).

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

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

3.1 General architecture of the IMACLIM-R model

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

IMACLIM-R is a model of the world economy[2] that covers the period 2001-2100 in yearly steps through the recursive succession of annual static equilibria and dynamic modules (Figure 1).

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

[Insert Figure 1 here]

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

3.2 Modeling the dynamics of the transportation sector

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

3.2.1 Passenger mobility demand

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

$$\begin{aligned} \boldsymbol{U} &= \left[\prod_{\text{goods i}} \left(\mathrm{C_i} - C_i^{(0)} \right)^{\xi_i} \right] . \left(S_m - S_m^{(0)} \right)^{\xi m} \\ \text{where } \boldsymbol{S}_m &= \left[\sum_{\text{modes j}} \left(\frac{\boldsymbol{pkm}_j}{b_j} \right)^{\eta} \right]^{\frac{1}{\eta}} \end{aligned} \tag{1}$$

Here, the aggregate mobility service S_m is defined as a CES composite of pasengers.km in the four modes under consideration (air, road, public[3], and non-motorized) with the elasticity of substitution between modes η and mode-specific parameters b_j. The basic needs of mobility $S_m^{(0)}$ measures constrained mobility (ie the minimum level that households have to satisfy, essentially for commuting) and ξ_m is the elasticity of utility to the level of mobility service.

Households maximize utility under a twofold constraint that affects transportation decisions. On the one hand, the standard budget constraint (2) captures that transport-related expenditures enter into a tradeoff with the consumption of other goods C_i paid at price p_i. The mobility services provided by public and air transport modes are paid at their end-use prices, p_{public} and p_{air} respectively, including fuel, O&M and capital costs. On the contrary, private modes are auto-produced by households at an end-use price that only includes liquid fuels (or electricity) costs (paid at prices p_{liquid} and p_{elec} respectively), given aggregate unitary consumption per unit of distance, α_{liquid}^{cars} and α_{elec}^{cars}. Note that fixed costs associated to car ownership do not enter into this tradeoff, but are considered in households investments. The income constraint can then be written as

$$Income = \sum_i p_i \cdot C_i + p_{public} \cdot pkm_{public} + p_{air} \cdot pkm_{air} + \left(\alpha_{liquid}^{cars} \cdot p_{liquid} + \alpha_{elec}^{cars} \cdot p_{elec}\right) pkm_{cars} \qquad (2)$$

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

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

In equation (3), $v_j(u)$ measures the marginal speed of transportation mode *j*, that is the speed for one additional passenger-kilometer. This variable depends on congestion effect, as measured by the utilization rate of transportation capacities for mode *j*, $Captransport_j$: the higher the utilization rate, the lower the effective "speed" of the mode (Figure 2). This representation is an extrapolation, at a very aggregated level, of the “macroscopic fundamental diagram” on the relations between vehicles fluxes, speed and infrastructure capacity at the scale of a large transportation network (Geroliminis and Danganzo, 2008). This curve is specific to each mode with, for example, very little (strong) effect for rail passenger (road) transport[4].

[Insert Figure 2 here]

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

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

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

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

3.2.2 Freight mobility demand

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

3.2.3 Transportation technologies and energy efficiency

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

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

Energy efficiency for freight transportation is not represented through explicit vehicle technologies but is captured implicitly through the evolution of the input-output coefficients measuring, for each mode (water, air and terrestrial transport), the energy requirements for the production of final transportation goods. These coefficients are responsive to energy price variations to capture the incentive for technical progress in function of market conditions (for example, the average fuel consumption of trucks evolves with a (-0.3) price-elasticity).

4 –Low carbon society and the transportation sector

4.1 Definition of the scenarios

To quantitatively assess the role of targeted policies for the transportation sector in the transformation to low carbon societies, two sets of scenarios are compared. Both correspond to the same climate objective, as captured by an identical emission trajectory corresponding to a stabilization target of 440–485 ppm CO2: global CO2 emissions peak in 2017 and are decreased by 20% and 60% with respect of 2000 level in 2050 and 2100, respectively (Barker et al. 2007, Table TS2). Each year, the model finds the level of carbon tax that constrains emissions to the exogenous target given for that period, tax revenues are recycled in a lump-sum manner within each region[5].

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

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

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

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

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

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

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

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

The modeling experiment then comprises:

- 48 BAU scenarios, corresponding to scenarios for which there is no constraint on CO2 emissions.
- 48 S1 stabilization scenarios, corresponding to stabilization scenarios with a "carbon price only" strategy.
- 48 S2 stabilization scenarios, where "transportation policies" are implemented as complementary measures to the carbon price.

These scenarios delineate the uncertainty on (i) Oil and Gas supply, (ii) coal supply, (iii) substitutes to oil, (iv) technological change and technologies potentials and costs, (v) lifestyles evolutions (see more details in (Waisman et al., 2012)). Here, we focus on the transportation sector, and its interactions with the rest of the economy, to disentangle the mechanisms at play in the alternative dynamics of passengers' transportation (Section 4.2) and freight transportation (Section 4.3), and analyze how the impacts of these alternative dynamics impact the rest of the economy (Section 4.4).

4.2 Climate policy and Passenger transport

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

[Insert Table 1 here]

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

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

[Insert Table 2 here]

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

[Insert Table 3 here]

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

[Insert Figure 3 here]

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

4.3 Climate policy and Freight transportation

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

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

[Insert Table 4 here]

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

[Insert Figure 4 here]

[Insert Figure 5 here]

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

4.4 The transportation sector in low carbon transitions: macroeconomic implications

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

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

[Insert Table 5 here]

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

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

[Insert Figure 6 here]

In S1, very high carbon price are necessary in the second part of the 21st century to reach the 450 ppm target via the proposed emission trajectory: in 2100, the average price across scenarios reach almost 600 \$/tCO_2 with a risk of attaining 1200\$/tCO2 under the most pessimistic technological assumptions. Waisman et al. (2012) showed that this high carbon price is associated with high macroeconomic losses reaching on average 4.6% of BAU GDP in 2100. The important long-term macroeconomic losses can be explained by (i) the inertia of infrastructures, location choices, and urban forms embedded in the model, and (ii) by the important rebound effect of mobility that requires very high carbon prices in the second half of the century to meet stringent emissions targets. In other words, lack of change in infrastructure and associated demand dominate the cost assessment in the long-run, since all the sectors other than transportation have already made substantive cuts in their emissions.

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

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

5. Conclusion

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

Transport proves to be the sector for which carbon emissions are the more difficult to reduce and hence represents a dominant share of remaining emissions in the long-term. Because of its weak reactivity to energy price increases, very high levels of carbon price must be imposed in the second half of the century to reach low mitigation targets: in 2100, the average value of carbon prices is around 600$/tC02, with a risk of attaining 1200$/tCO2.

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

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

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

References

Åkerman, J., and M. Höjer. 2006. « How much transport can the climate stand?—Sweden on a sustainable path in 2050 ». Energy policy 34 (14): 1944-1957.

Allcott, H, 2010, 'Beliefs and Consumer Choice' , Working Paper MIT (December).

Allcott, H, Wozny, N., 2011,'Gasoline Prices, Fuel Economy, and the Energy Paradox.' Working Paper MIT (July).

Allcott, H., 2011. 'Consumers' Perceptions and Misperceptions of Energy Costs.', American Economic Review, Papers and Proceedings, 101(3), 98-104.

Anable, J, Brand, C, Tran, M, Eyre, N, 2012, "Modelling transport energy demand: A socio-technical approach", Energy Policy 41,125–138

Anable, Jillian, Sally Cairns, Lynn Sloman, Phil Goodwin, Alistair Kirkbride, and Carey Newson. 2005. « 'Soft' Measures – soft option or smarter choice for early energy savings in the transport sector? » 671-685.

Anderson, S., Kellogg, R, Sallee, J., 2011, What Do Consumers Believe About Future Gasoline Prices?, NBER Working Paper No. w16974

Banister, David. 2000. European Transport Policy and Sustainable Mobility. Taylor & Francis.

Barkenbus, J, 2010.' Eco-driving: An overlooked climate change initiative', Energy Policy 38 (2), 762–769

Barker T, Bashmakov I, Bernstein L, Bogner JE, Bosch PR, Dave R, Davidson OR, Fisher BS, Gupta S, Halsnæs K, Heij GJ, Kahn Ribeiro S, Kobayashi S, Levine MD, Martino DL, Masera O, Metz B, Meyer LA, Nabuurs G-J, Najam A, Nakicenovic N, Rogner HH, Roy J, Sathaye J, Schock R, Shukla P, Sims REH, Smith P, Tirpak DA, Urge-Vorsatz D, Zhou D (2007): Technical Summary. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Bento, A. M., M. L. Cropper, A. M. Mobarak, and K. Vinha. 2005. « The effects of urban spatial structure on travel demand in the United States ». Review of Economics and Statistics 87 (3): 466-478.

Bieber, A., Massot, M.-H., Orfeuil, J.-P., 1994. 'Prospects for daily urban mobility'. Transport Reviews 14 (4), 321–339.

Bristow, Abigail L., Miles Tight, Alison Pridmore, and Anthony D. May. 2008. « Developing pathways to low carbon land-based passenger transport in Great Britain by 2050 ». Energy Policy 36 (9) (septembre): 3427-3435. doi:10.1016/j.enpol.2008.04.029.

Brand, C, Tran, M, Anable, J, 2012, The UK transport carbon model: An integrated life cycle approach to explore low carbon futures Energy Policy 41, 107–124

Brueckner, J. K. 2000. « Urban sprawl: Diagnosis and remedies ». International regional science review 23 (2): 160-171.

Cairns, S., L. Sloman, C. Newson, J. Anable, A. Kirkbride, and P. Goodwin. 2004. « Smarter choices-changing the way we travel ».

Cairns, S., L. Sloman, C. Newson, J. Anable, A. Kirkbride, and P. Goodwin. 2008. « Smarter choices: assessing the potential to achieve traffic reduction using ‘soft measures’ ». Transport Reviews 28 (5): 593-618.

Chapman, L. 2007. « Transport and climate change: a review ». Journal of transport geography 15 (5): 354-367.

Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, Gabrielle B, Goss Eng A, Lucht W, Mapako M, Masera Cerutti O, McIntyre T, Minowa T and Pingoud K (2011). Bioenergy. In: O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner,, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds) IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation , Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Dahl, C, 2012,‘Measuring global gasoline and diesel price and income elasticities’ ,Energy Policy, 41, 2-13

Dargay, J., Gately, D., Sommer, M., 2007, ‘Vehicle ownership and income growth, worldwide: 1960–2030’, Energy Journal, 28, 143–170

Dimaranan, B., and R. A. McDougall. 2006. Global Trade, Assistance and Production: The GTAP 6 Data Base, Center for Global Trade Analysis. Purdue University, West Lafayette, IN.

Geroliminis, N., and C. F. Daganzo. 2008. « Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings ». Transportation Research Part B: Methodological 42 (9): 759-770.

Glaeser, Edward L., and Matthew E. Kahn. 2010. « The greenness of cities: Carbon dioxide emissions and urban development ». Journal of Urban Economics 67 (3) (mai): 404-418. doi:10.1016/j.jue.2009.11.006.

Goodwin, P, Dargay, J, Hanly, M,2004, ‘Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income: A Review’.Transport Reviews 24 (3), 275-292.

Goodwin, P. B. 1996. « Empirical evidence on induced traffic ». Transportation 23 (1): 35-54.

Grazi, Fabio, Jeroen C.J.M. van den Bergh, and Jos N. van Ommeren. 2008. « An Empirical Analysis of Urban Form, Transport, and Global Warming ». The Energy Journal 29 (4) (octobre 1). doi:10.5547/ISSN0195-6574-EJ-Vol29-No4-5. http://www.iaee.org/en/publications/ejarticle.aspx?id=2279.

Greene, D, 1998, ‘Why CAFE worked?’,Energy Policy,26(8), 595–613

Greene, D. L., S. E. Plotkin, and Pew Center on Global Climate Change. 2011. Reducing greenhouse gas emissions from US transportation. Pew Center on Global Climate Change Washington, DC.

Greening, L, Greene, D , Difiglio, C ,2000,‘Energy efficiency and consumption – the rebound effect – a survey’,Energy Policy, 28(6), 389-401.

Hickman, R., O. Ashiru, and D. Banister. 2011. « Transitions to low carbon transport futures: strategic conversations from London and Delhi ». Journal of Transport Geography.

Hickman, Robin, Olu Ashiru, and David Banister. 2010. « Transport and climate change: Simulating the options for carbon reduction in London ». Transport Policy 17 (2) (mars): 110-125. doi:10.1016/j.tranpol.2009.12.002.

Holden, E., and I. T. Norland. 2005. « Three challenges for the compact city as a sustainable urban form: household consumption of energy and transport in eight residential areas in the greater Oslo region ». Urban Studies 42 (12): 2145.

Hourcade, JC, Jaccard, M, Bataille, C et Ghersi, F, 2006, 'Hybrid Modeling : New Answers to Old

Hourcade, J-C., 1993, 'Modelling long-run scenarios. Methodology lessons from a prospective study on a low CO2 intensive country', Energy Policy, 21(3), 309-326.

Hymel, K. M., K. A. Small, and K. V. Dender. 2010. « Induced demand and rebound effects in road transport ». Transportation Research Part B: Methodological 44 (10): 1220-1241.

IEA, 2011a, CO2 Emissions from Fuel Combustion, OECD, Paris.

IEA, 2011b, World Energy Outlook 2011 , OECD,Paris.

International Energy Agency. 2009. « Transport, Energy and CO2: Moving Toward Sustainability ». OECD/IEA.

International Transport Forum, 2007. Workshop on ecodriving: findings and messages for policy makers, November 22–23. Available at: http://www.internationaltransportforum.org/Proceedings/ecodriving/EcoConclus.pdf

IPCC (2007). Summary for Policymakers. In: B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds) ,

Johansen L., 1959, "Substitution versus Fixed Production Coefficients in the Theory of Growth: A synthesis", Econometrica, 27, 157-176.

Johansson, Bengt. 2009. « Will restrictions on CO2 emissions require reductions in transport demand? » Energy Policy 37 (8) (août): 3212-3220. doi:10.1016/j.enpol.2009.04.013.

Le Néchet, Florent. 2011. « Consommation d'énergie and mobilité quotidienne selon la configuration des densités dans 34 villes européennes. » Cybergeo : European Journal of Geography (mai 18). doi:10.4000/cybergeo.23634. http://cybergeo.revues.org/23634.

Malcolm,G, Truong, P, 1999,'The Process of Incorporating Energy Data into GTAP', Draft GTAP

McCollum, David, and Christopher Yang. 2009. « Achieving deep reductions in US transport greenhouse gas emissions: Scenario analysis and policy implications ». Energy Policy 37 (12) (décembre): 5580-5596. doi:10.1016/j.enpol.2009.08.038.

McKinnon, Alan. 2010. Green Logistics: Improving the Environmental Sustainability of Logistics. Kogan Page Publishers.

Metz, D. 2008. « The myth of travel time saving ». Transport Reviews 28 (3): 321-336.

Mindali, Orit, Adi Raveh, and Ilan Salomon. 2004. « Urban density and energy consumption: a new look at old statistics ». Transportation Research Part A: Policy and Practice 38 (2) (février): 143-162. doi:10.1016/j.tra.2003.10.004.

Mokhtarian, P., Chen, C., 2004. 'TTB or not TTB, that is the question: a review and analysis of the empirical literature on travel time (and money) budgets', Transportation Research Part A, 38, 643-675.

Muñiz, I., and A. Galindo. 2005. « Urban form and the ecological footprint of commuting. The case of Barcelona ». Ecological Economics 55 (4): 499-514.

Newman, Peter WG, and Jeffrey R Kenworthy. 1996. « The land use—transport connection: An overview ». Land Use Policy 13 (1) (janvier): 1-22. doi:10.1016/0264-8377(95)00027-5.

NHTS, 2009, 'Summary of travel trends: 2009 National Household Travel', available at http://nhts.ornl.gov/2009/pub/stt.pdf.

Nivola, P., 1999, 'The Law of the Landscape:How Policies Shape Cities in Europe and America', Brookings Metropolitan, Washington, D.C.

Noland, Robert B. 2008. « Understanding Accessibility and Road Capacity Changes: A Response in Support of Metz ». Transport Reviews 28 (6): 698-706. doi:10.1080/01441640802535995.

Owens, S, 1986,Energy, Planning and Urban Form, Pion Ltd, Great Britain

Piecyk, M. I., and A. C. McKinnon. 2010. « Forecasting the carbon footprint of road freight transport in 2020 ». International Journal of Production Economics 128 (1): 31-42.

Sands RD, Miller S and Kim MK (2005). The Second Generation Model: Comparison of SGM and GTAP

Santos, Georgina, Hannah Behrendt, and Alexander Teytelboym. 2010. « Part II: Policy instruments for sustainable road transport ». Research in Transportation Economics 28 (1): 46-91. doi:10.1016/j.retrec.2010.03.002.

Schäfer, A., 2012, Introducing Behavioral Change in Transportation into Energy/Economy/Environment Models. Draft Report for •"Green Development•" Knowledge Assessment of the World Bank.

Schäfer, A, Heywood, J.B., Jacoby, H.D,Waitz, I.A, 2009. Transportation in a Climate-Constrained World: The MIT Press.

Schafer, A., Victor, D., 2000, 'The future mobility of the world population',Transp Research A, 34(3), 171-205.

Schafer, A., 1998, 'The global demand for motorized mobility',Transp Research A, 32(6), 455-477

Searchinger, T., R. Heimlich, R. A Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. H Yu. 2008. « Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change ». Science 319 (5867): 1238-1240.

Shalizi, Z., Lecocq., F., 2009. 'Climate change and the economics of targeted mitigation in sectors with long-lived capital stock'. Policy Research Working Paper 5063, Washington D.C.: World Bank

Smokers, Richard, Ab de Buck, and Margaret van Valkengoed. 2009. « Marginal abatement costs for greenhouse gas emission reduction in transport compared with other sectors ». Delft, CE Delft.

Tilman, D., R. Socolow, J. A. Foley, J. Hill, E. Larson, L. Lynd, S. Pacala, J. Reilly, T. Searchinger, and C. Somerville. 2009. « Beneficial biofuels—the food, energy, and environment trilemma ». Science 325 (5938): 270-271.

Turrentine, T, Kurani, K, 2007,' Car buyers and fuel economy?', Energy Policy,35, 1213–1223

UK Committee on Climate Change. 2008. « BUILDING A UK TRANSPORT SUPPLY-SIDE MARGINAL ABATEMENT COST CURVE ».

United Nations, Department of Economic and Social Affairs, Population Division, 2012. World 'Urbanization Prospects: The 2011 Revision', available at: http://esa.un.org/unpd/wup/CD-ROM/Urban-Rural-Population.htm

Vilhelmson, B., 1999. 'Daily mobility and the use of time for different activities: the case of Sweden'. GeoJournal 48, 177– 185.

Waisman, H, Guivarch, C, Grazi, F, Hourcade, J-C, 2012,'The Imaclim-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight ', Climatic Change, accepted for publication, on-line first (http://www.springerlink.com/content/22jk123872580154/)

Wang, H., P. Zhou, and D.Q. Zhou. 2012. « An empirical study of direct rebound effect for passenger transport in urban China ». Energy Economics 34 (2) (mars): 452-460. doi:10.1016/j.eneco.2011.09.010.

Zahavi, Y., Talvitie, A., 1980,'Regularities in Travel Time and Money Expenditures',Transportation Research Record,750, 13-19

Endnotes

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

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

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

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

$v_j(x) = \frac{v_0}{a \cdot x^{\alpha} + 1}$. Parameters values are calibrated such that (i) v_0 equals 700, 80 and 50 km/h for air transportation, cars and public transport respectively, (ii) $v_j(1) = v_1$, with v_1 equals 5 km/h for all modes, (iii) the households maximization program results in observed data on mobility and budget shares per mode for the calibration year 2001.

5. This simplified representation of climate policies means that we ignore some dimensions that may affect the cost of climate policies: the intertemporal flexibility for allocating emission reductions ("when flexibility"), international redistribution of carbon tax revenues or internal recycling towards a reduction of labor taxes. See IPCC (2007) for an overview on these questions.

List of Tables

Table 1: *CO_2 emissions (in $GtCO_2$) 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. 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]

Table 2: *Global mobility, in passenger.kilometers per capita in 2010, 2050 and 2100 in BAU, 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]

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.*

		2050			2100		
	2010	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%

Table 4: *CO_2 emissions (in Gt CO_2) 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	
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]

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.*

		2010-2050		2050-2100	
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]

List of Figures

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

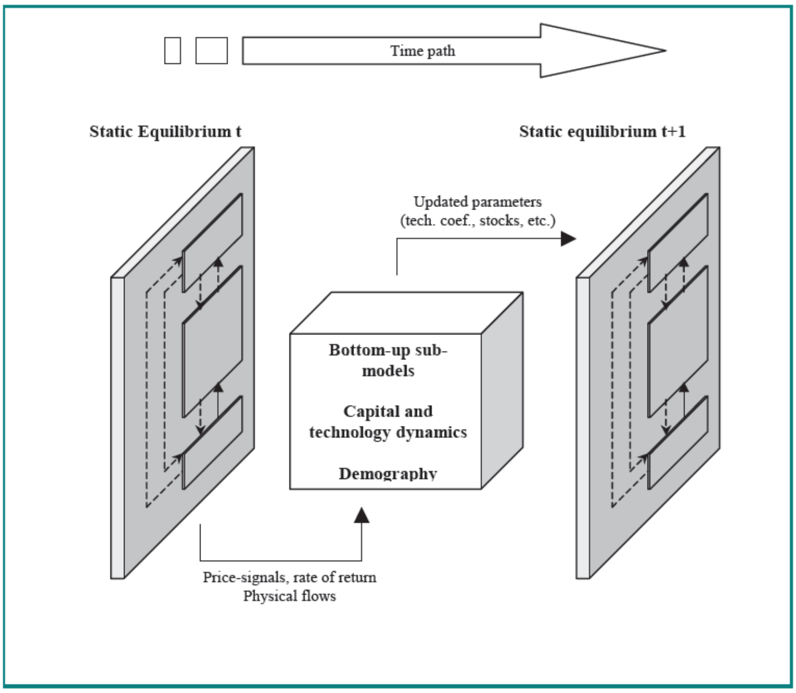


Figure 2. *Marginal time efficiency of transportation mode j*

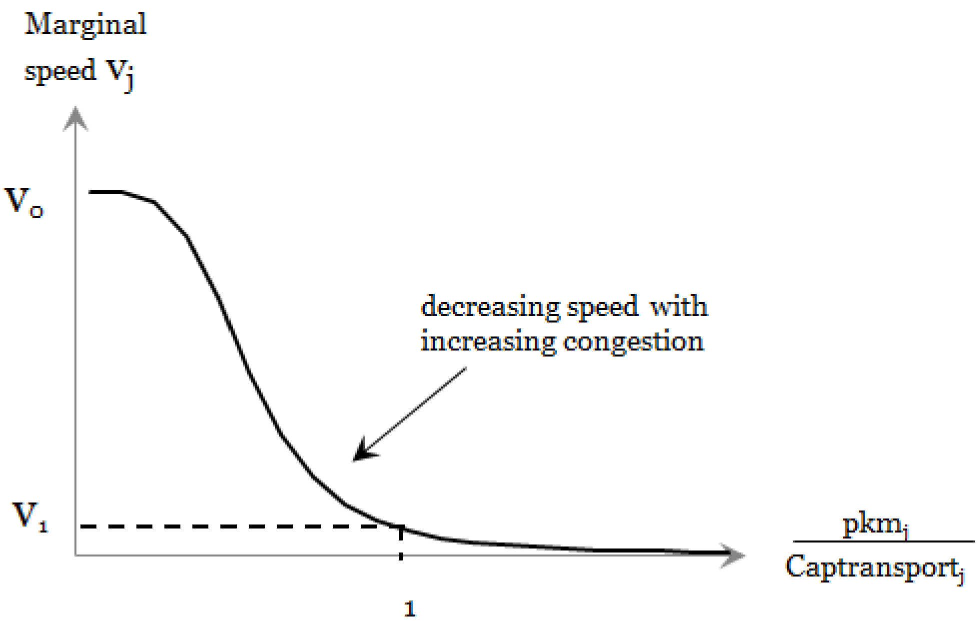


Figure 3: *Mean liquid fuel consumption of the personal vehicle fleet over 2000-2100 in BAU (black), in S1 (blue) and S2 (red) scenarios, as an index of 2000 level. Average values are in bold lines.*

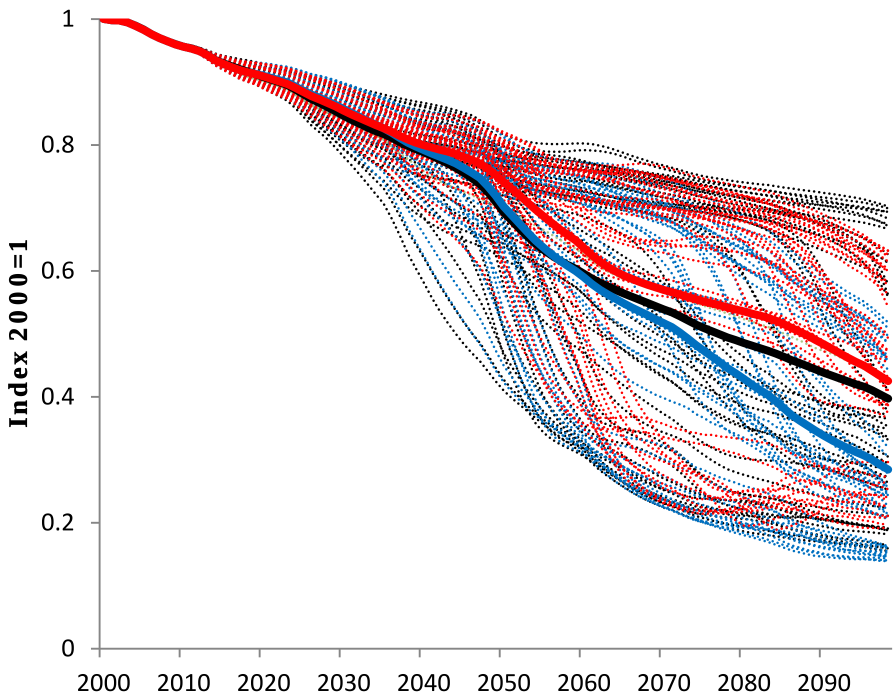


Figure 4: *Global inland freight transportation activity index (ton.kilometers) over 2000-2100 in BAU (black), in S1 (blue) and S2 (red) scenarios. Average values are in bold lines.*

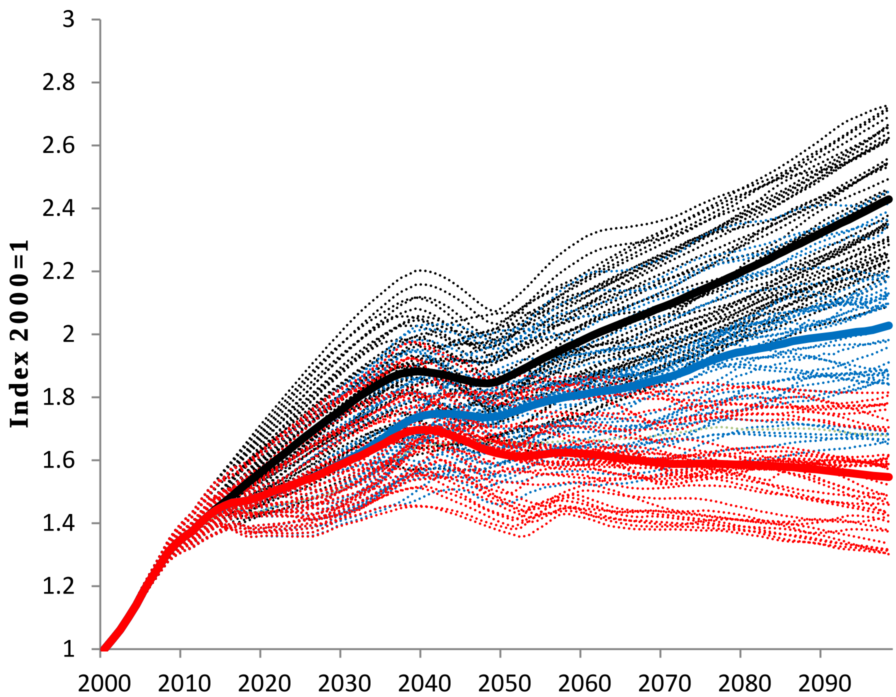


Figure 5: *Inland freight transportation liquid fuel consumption per ton.kilometerover 2000-2100 in BAU (black), in S1 (blue) and S2 (red) scenarios, as an index of 2000 level. Average values are in bold lines.*

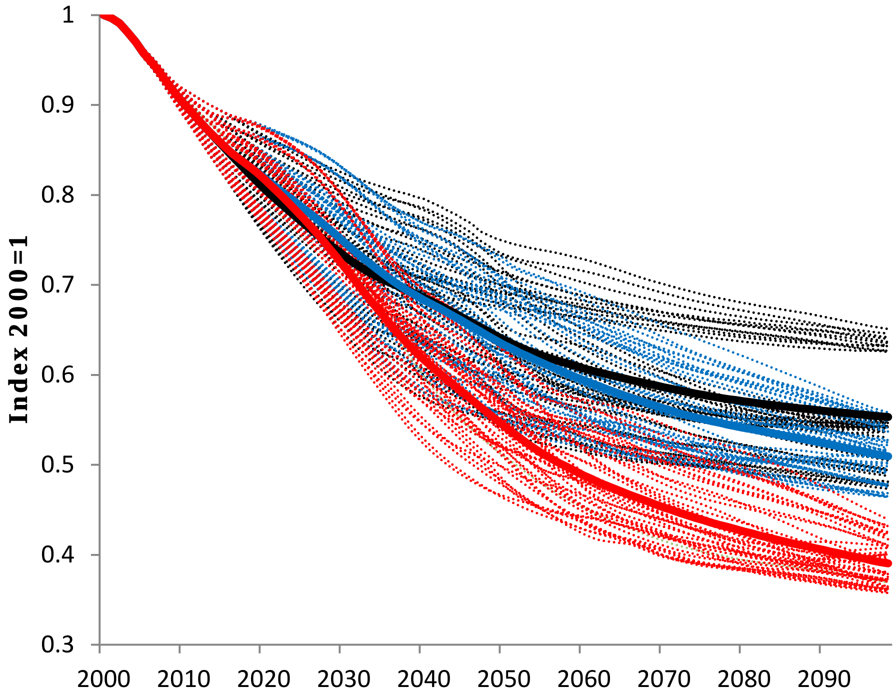
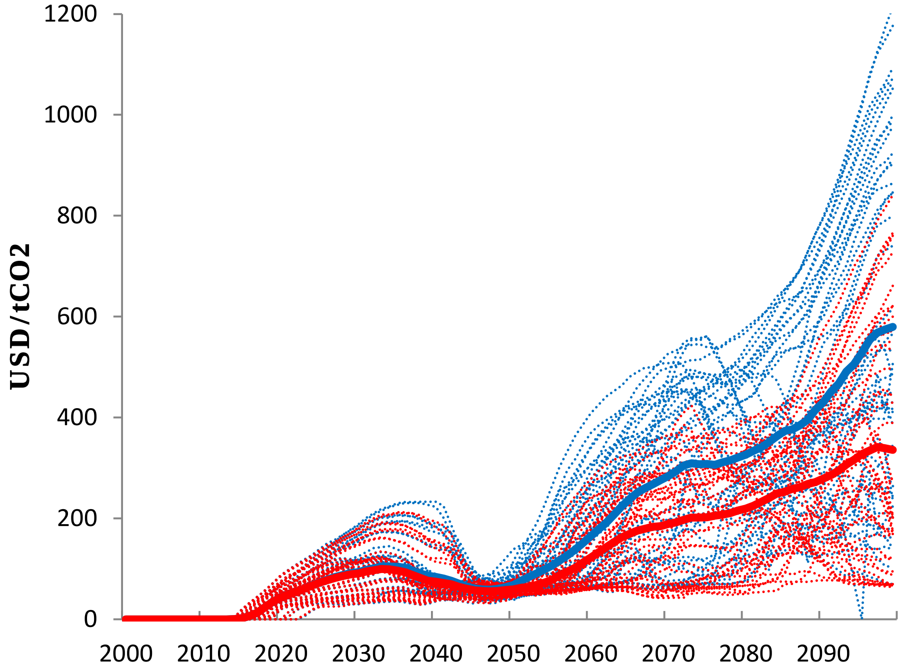


Figure 6: Price path of carbon (in [constant 2010] U.S. dollars/tCO_2) in S1 (blue) and in S2 (red) scenarios. Average values in bold lines.


USD/tCO2
1200
1000
800
600
400
200
0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090