sustainability

MDPI

Supplementary Material: The transportation sector in the IMACLIM-R model: a way to embark energy consumption and urban organizations

This Supplementary Material is a complement to the article "Low carbon scenarios for Europe. An evaluation of upscaling low carbon experiments". It presents the way the IMACLIM-R model represents the transport sector and is an adaptation of material included in [1].

1. Passenger mobility demand: a result of households' utility maximization program

IMACLIM-R is a general equilibrium model where a representative household (representative consumer) maximizes its utility function under an income budget constraint and a travel time budget constraint. The existence of two budget constraints in addition to the originality of the arguments of this utility function allow capturing the induction of final demand by technical change and infrastructure policies, especially in the energy and transportation sectors.

Households maximize their utility through a tradeoff between consumption goods and mobility services. More precisely, they derive utility from:

- The consumption of goods ***i*** above its minimum level $\mathrm{C_i} - C_i^{(0)}$. The "goods" consumed are those produced by the agriculture, industry and services sectors.
- Mobility services above their minimum level $S_m - S_m^{(0)}$. The basic needs of mobility $S_m^{(0)}$ measures constrained mobility (i.e. the minimum level that households have to satisfy, mainly for commuting). Note that this minimum level allows capturing implicitly the urban sprawl.

The utility function is thus written as:

$$\boldsymbol{U} = \left[\prod_{\text{goods i}} \left(\mathrm{C_i} - C_i^{(0)} \right)^{\xi_i} \right] . \left(S_m - S_m^{(0)} \right)^{\xi_m} \tag{1}$$

Where parameters ξ_i and ξ_m are the elasticities of utility to the level of goods' consumption and of mobility service respectively.

To provide the mobility service, four transportation modes are considered:

- Terrestrial public transport[1]
- Air transport
- Road transport (private vehicles)
- Non-motorized transport (walking and biking)

One can note that the representation of non-motorized transportation is for IMACLIM the way to embark the transport dimension of human energy.

The four modes are imperfect substitute mostly because of the differences in amenities delivered by each of them. They are thus nested in a constant elasticity of substitution (CES) function. The aggregate mobility service S_m is defined as a composite of passenger.km in the four transportation modes under consideration:

$$\boldsymbol{S_m} = \left[\sum_{\text{modes j}} \left(\frac{\boldsymbol{pkm_j}}{b_j} \right)^{\eta} \right]^{\frac{1}{\eta}} \tag{2}$$

[1] "Public transport" includes both urban public transports (buses, metros… etc.) and inter-city trains because the model does not differentiate between inter- and intra-city trips.

Where η is the elasticity of substitution between the modes, and b_j are mode-specific parameters. Households' transportation decisions are constrained by:

(i) A standard income budget constraint (3)

This constraint captures that transport-related expenditures enter into a tradeoff with the consumption of other goods and services 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 (these prices include fuel, capital and Operating & Maintaining costs), whereas private modes, that are auto-produced by households, involve only the purchase of liquid fuels or electricity[2] that are respectively paid at prices p_{liquid} *and* p_{elec}. Given α_{liquid}^{cars} and α_{elec}^{cars}, the unitary consumptions of liquid fuels and electricity per unit of distance (passenger.km), the income constraint can be written as:

$$Disposable\ Income = \sum_i p_i \cdot C_i + p_{public} \cdot pkm_{public} + p_{air} \cdot pkm_{air} + \left(\alpha_{liquid}^{cars} \cdot p_{liquid} + \alpha_{elec}^{cars} \cdot p_{elec}\right) pkm_{cars} \quad (3)$$

(ii) A travel time budget constraint (4)

As it has been observed empirically, this constraint represents the regularity in travel time budget across time and space. Number of studies demonstrates indeed that at an aggregate and average level, households allocate a fixed amount of time to transportation, regardless of transportation costs (see for example [2-5][3]. In particular [6,2], using samples of cities in developed and developing countries observed that a traveler spend between 1 and 1.5 hours per day in transports (the value determined for Europe is 1.1hour). For the sake of simplicity and given the level of aggregation considered here, we assume that this time constraint governs both intra and inter-city trips, and that it concerns rural areas as well as urban ones.

This time constraint plays with the households' demand for transportation services as well as the modal share between the four modes considered, it can be written as:

$$T_{disp} = \sum_{\text{Modes j}} \int_0^{pkm_j} \frac{du}{v_j(u)} \quad (4)$$

Where $v_j(u)$ measures the marginal speed of transportation mode *j* (i.e. the speed for an additional passenger-kilometer). For each mode *j*, this speed $v_j(u)$ is linked to congestion effects and can be written as a function of the utilization rate of transportation capacities $Captransport_j$ as captured by figure 4: the higher the utilization rate, the lower the effective speed of the mode and the higher congestion.

---

[2] Fixed costs associated to car ownership are considered in households' investments and do not enter into this consumption tradeoff.

[3] Controversies can be found in the literature in [7]. However, even them, they support the existence of a constant travel time budget when the level of aggregation is sufficiently high.

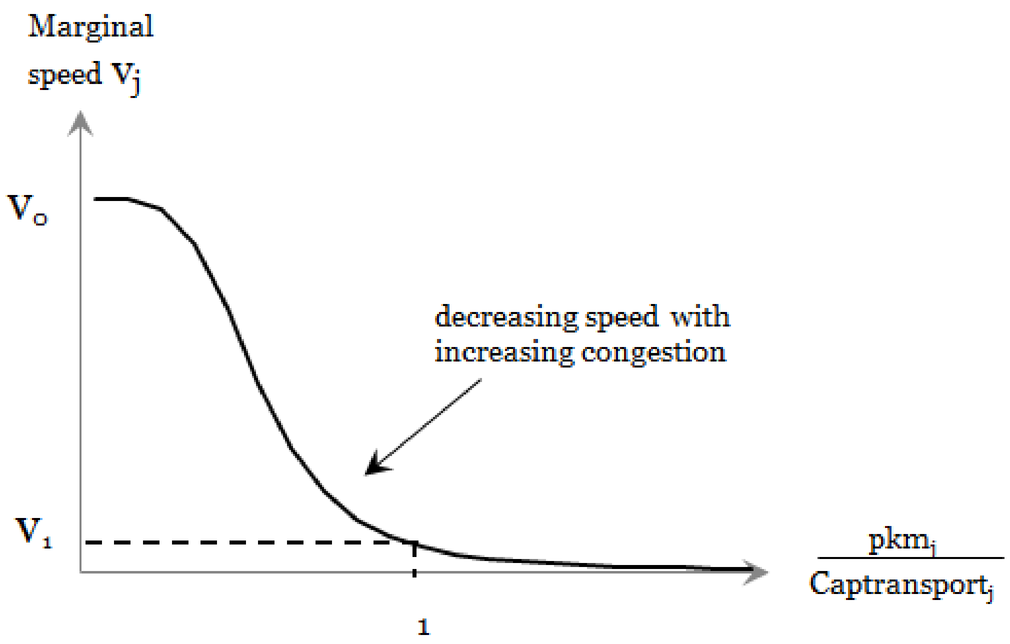

Figure 1: Marginal speed and the utilization of the transportation infrastructure capacity.

(Subscript **j** denotes the transportation mode j)

This curve is specific to each mode with, for example, very strong effect for road passenger transport and conversely very little effect for rail passenger transport.

This representation is an extrapolation, at a high aggregated level, of the "macroscopic fundamental diagram" that gives a relation between vehicle traffic fluxes and traffic density (speed and infrastructure capacity) at the scale of a large transportation network [8].

The form chosen is:

$$v_j\left(x_j\right) = \frac{v_{j0}}{a \cdot x_j^{\alpha} + 1} \quad \text{with} \quad x_j = \left(\frac{pkm_j}{Captransport_j}\right)$$

Parameters values are calibrated such that:

(i) v_0 equals 700, 80 and 50 km/h for air, cars and public transport respectively.

(ii) $v_j\left(1\right) = v_1$ that equals 5km/h for all modes.

(iii) the households maximization program results in observed data on mobility and budget shares per mode for the calibration year.

Important stylized facts of passenger mobility can be captured thanks to this twofold constraint structure:

- The ***rebound effect*** on mobility due to energy efficiency improvements: More efficient vehicles trigger lower households' fuel expenditures and thus free up resources to increase the overall consumption, and the mobility demand in particular. The budget constraint *(3)* allows indeed capturing this effect and shows that higher disposable households' income allows an increase of all goods and services consumption, including demand for transportation.
- The ***induction effect*** of infrastructure deployment on mobility demand: For a given transportation mode, the deployment of new additional infrastructures increases the capacity of the corresponding network and decreases the congestion constraint. The

marginal effect of infrastructure deployment depends on the shape of the congestion curve (Figure 2). The average speed allowed by the available infrastructures is thus higher and the passenger.kilometers in that mode are less time-consuming. This allows households to increase their overall travel demand within their time budget constraint *(4)*.

- The ***modal distribution*** between different modes: The four considered modes (air, road, public and non-motorized) are explicitly differentiated according to their *(i)* costs, *(ii)* provided mobility service measured by their average speed, and *(iii)* the availability of infrastructures that determine congestion levels. Effective modal distribution then results endogenously from a tradeoff within the twofold constraint: income budget *(3)* and travel time budget *(4)*.
- The ***constrained mobility*** induced by firms' and households' localization choices: This concerns daily travels that households have no choice but to realize to satisfy specific travel purposes (essentially commuting and shopping). They are exogenously represented by the basic needs parameter $S_m^{(0)}$ in equation *(1).*

Note that from all this appear a positive feedback loop in the transportation sector between technical choices, households' modal choices and overall mobility demand.

1.1. Freight mobility demand: a result of a Leontief representation

In IMACLIM-R, production functions of all the sectors take the form of Leontief specifications, with fixed equipment stocks and fixed intensity of labour, energy and other intermediary inputs in the short-term[4]. This means in particular that, at a given point in time, the freight transportation intensity of production is measured by input-outputs coefficients $IC_{j,Sec}$, which define a linear dependence of freight mobility in a given mode *j* to production volumes of sector *Sec*. The higher the production volumes, the higher the freight mobility demand if no specific policy towards reducing this volume is implemented.

Three freight transportation modes are considered: **air, water and terrestrial transport**. The latter includes both trucks and rail modes because of data limitations. The two modes correspond indeed to a single aggregated sector in the GTAP 6 economic accounting matrixes used for the IMACLIM-R calibration [9].

This freight mobility representation *via* input-output coefficients of production captures implicitly two important features that drive the modal breakdown and the intensity of freight mobility needs:

(i) The spatial organization of the production processes in terms of specialization/concentration of production units

(ii) The constraints imposed on distribution in terms of distance to the market and just-in-time processes

Furthermore, the input-output coefficients $IC_{j,Sec}$ evolve in time[5] to capture changes in:

(i) The energy efficiency of freight vehicles

(ii) The logistic organization of the production/distribution processes

(iii) The modal breakdown

---

[4] These Leontief specifications (with fixed inputs per unit of production) are nevertheless characterized by flexible utilization rates of installed production capacities.

[5] They evolve in a "putty-clay" modeling way [10]

1.2. Energy efficiency in the transportation sector

Transportation technologies within the private motorized mobility:

Within the personal vehicles market, three types of technologies are represented:

- Internal combustion engine standard (ICE_std)
- Efficient internal combustion engine (ICE_eff)
- Electrical vehicles (EV)[6]

The description of these transport technologies remains at a rather aggregated level to facilitate the dialogue with the top-down macroeconomic description. Each technology is specified as a set of:

(i) *apital cost*, which decreases endogenously in function of learning-by-doing process. We use learning curves to represent induced technical change; they link decrease in capital cost to the cumulative sale of a given technology.

(i) *Operating and maintaining (O&M) costs*, that are considered as variable costs and modelled as a quantity of composite sector consumed per unit of travelled distance, and finally

(ii) *Energy intensity*.

The energy consumption (in liters of gasoline equivalent by kilometer, lge/km) is related to conventional gasoline and diesel, but also to biofuels and synfuels as Coal-to-Liquid fuel (CTL) or electricity. Instead of having specific car technologies for each liquid fuel type, those are supposed to be mixable with refined oil. This means that non-electrical vehicles can run equally well on a blend of CTL, biofuel or diesel/gasoline. Note that we do not explicitly take plug-in Hybrid vehicles into account, and that only Electric vehicles consume electricity.

Energy efficiency in private vehicles

It is measured by the evolution the parameters α_{liquid}^{cars} and α_{elec}^{cars} in equation *(3)*, which result from households' decisions on the purchase of new vehicles among the three types of technologies. These decisions are based on a mean cost minimization criterion under imperfect expectations. More precisely, the dynamic of the evolution of these energy efficiency parameters is the following:

- Each year, an endogenous motorization rate (number of personal vehicle per capita) is computed as a region specific function of personal income. Its income elasticity varies in function of income levels [11]. For Europe (high income level compared to developing regions), the elasticity decreases progressively to represent equipment saturation (it is assumed in particular that the motorization rate never exceeds the current US value which equals to 0.7 vehicle per person). Numerical values for this income elasticity are adjusted from the SMP Model [12].
- Based on this motorization rate, fleet depreciation is explicitly considered and derived from the described vintage car stocks and lifetimes. Sales are calculated as the sum of total equipment increment and the number of down run cars. They are then allocated amongst the different technologies as follows:
  - Households associate a complete life cycle cost (LCC) to each technology taking into account its capital cost, energy intensity, electricity and liquid fuel prices (including all taxes as well as an hypothetical carbon tax), O&M costs, the annual average travelled distance and a discount rate[7].
  - Market share of a given technology is then computed through a logit function on LCCs in order to avoid a market concentration in the most competitive vehicle and

[6] Electric vehicles represent implicitly all types of vehicles that use electricity as service provider, including fuel cells and hydrogen vehicles.

[7] We use a 13% discount rate, which reflects consumers' aversion to invest in more expensive but more efficient technologies, unless the financial payback time is short. Consistently with Imaclim-R simulation philosophy, a high discount rate represents actual consumers' perception rather than optimal economic choices.

to account for heterogeneous consumers' preferences as well as for the diversity of cars [13].

Finally, taking into account that only a small part of the fleet is replaced each year, the regional energy intensity parameters of the fleet are then calculated as a mean on all operating car vintages.

Note that energy efficiency improvement is thus encompassed at a macroeconomic scale in the sense that a growth of fuel prices induces a natural direction of households towards more energy efficient vehicles.

Energy efficiency for freight transportation

Unlike the private vehicle case, energy efficiency for freight transportation is not represented through explicit technologies but is captured through the evolution of Leontief coefficients. For each freight transportation mode (water, air and terrestrial transport), input-output coefficients measure the energy requirement for the production of final transportation goods. Their evolution is driven by an exogenous trend but also by a short-term fuel price elasticity (for example, the average fuel consumption of trucks evolves with a (-0.35) price-elasticity). These coefficients are thus responsive to energy price variations, which allow capturing endogenous energy efficiency gains, in other words, the incentive for technical progress in function of market conditions. Furthermore, since the terrestrial transport mode gathers both road and rail freight transport, this way of modelling allows also capturing the modal shifts that occur amongst this mode when fuel prices vary.

References

1. Cassen C., Hamdi-Chérif M. and Houcade J-C. Report on IMACLIM-R model experiments and analysis. 2015 Deliverable 4.1 of MILESECURE-2050. Avaiable online: http://www.milesecure2050.eu/en/public-deliverables (Accessed on 9 March 2018).
2. Zahavi, Y.; Talvitie, A. Regularities in Travel Time and Money Expenditures. *Transportation Research Record* **1980**, *750*, 13–19.
3. Bieber, A., Massot, M.-H., Orfeuil, J.-P. Prospects for daily urban mobility. *Transport Reviews* **1994**, *14*, 321–339.
4. Vilhelmson, B. Daily mobility and the use of time for different activities: the case of Sweden. *Geo. Journal* **1999**, 48, 177–185.
5. Schäfer, A.;Victor, D. The future mobility of the world population. *Transportation Research Part A* **2000**, *34*, 171–205.
6. Zahavi, Y. UMOT Project. Prepared for US Department of Transportation, Washington, DC and Ministry of Transport, Federal Republic of Germany, Bonn. Report DOT-RSPA-DPB-20-79-3, August 1979.
7. Mokhtarian, P.; Chen, C. 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* **2004**, *38*, 643–675.
8. Geroliminis, N.; Daganzo, C. F. Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings. *Transportation Research Part B: Methodological* **2008**, *42*, 759–770.
9. Dimaranan, B.; McDougall. R. A. Global Trade, Assistance and Production: The GTAP 6 Data Base. Center for Global Trade Analysis. Purdue University: West Lafayette, IN, USA, 2006.
10. Sassi, O.; Crassous, R.; Hourcade, JC.; Gitz, V.; Waisman, H.; Guivarch, C. IMACLIMR: a modelling framework to simulate sustainable development pathways, *IJGEnvI* **2010**, *10*, 5–24.
11. Dargay, J.; Gately, D.; Sommer, M. Vehicle ownership and income growth, worldwide: 1960–2030. The Energy Journal **2007**, *28*, 143–170.
12. Fulton, L.; Eads, G. IEA/SMP Model Documentation and Reference Case Projection, 2004 Available online: http://www.libralato.co.uk/docs/SMP%20model%20guidance%202004.pdf. (Accessed on 9 March 2018)
13. Horne, M.; Jaccard, M.; Tiedemann, K.Improving behavioral realism in hybrid energy-economy models using discrete choice studies of personal transportation decisions. *Energy Econ*. **2005**, *27*, 59–77.