Technical Report IMACLIM

Emissions estimation method

Emissions are computed ‘ex post’, on the basis of modelling results and assumptions from three distinct sources: the IMACLIM-R and POLES models produce a harmonised baseline of the global economy and energy markets up to 2050; the SMP model provides emission coefficients for 5 generic local pollutions from transportation activities—particulate matter, nitrogen oxides, volatile organic compounds, carbon monoxide and lead.

The following subsections first describe the three models, then give more detail about the method used to compute the emissions of the different types of vehicle accounted for. A last subsection describes the particular case of lead emissions.

Model description

IMACLIM-R (IMpact Assessment of CLIMate policies-Recursive version) is a dynamic recursive computable general equilibrium (CGE) model of the world economy. The version used in this study details 12 world regions, among which Europe,[1] and 10 economic sectors, among which air, sea, and land transportation activities as 3 distinct sectors. General economic growth mainly results from exogenous assumptions about population and labour productivity dynamics, however international trade—esp. of energy commodities—, and imperfect markets for both labour (wage curve) and capital (constrained capital flows, utilisation rate below 1), introduce an endogenous element. In this framework, transportation demands result from

- The intermediate consumption of transport by all sectors: the three transportation activities are inputs to the 10 productions detailed. In the current version of IMACLIM-R the input coefficients other than energy are fixed (the Leontief assumption), which leads to a development of intermediate transportation activities proportional to economic growth, or at least to the growth of each sector described.[2]
- Household demand, which is given a fairly elaborate specification: mobility, defined as an aggregate of 4 imperfectly substitutable travelling modes (air travel, public ground modes, personal cars and non motorised modes), is one of the arguments of the utility function of the representative household (one per region). Besides, on top of their budget constraint households are submitted to a travelling-time constraint.[3] Last but not least, the ‘travelling time efficiency’ (average distance covered in an hour time) of each mode is an increasing function of public investment in the infrastructure dedicated to this mode.

POLES (Prospective Outlook on Long Term Energy Systems) projects the energy systems of a 47-zone world every year up to a 2050 horizon, based on the main assumptions of GDP and population growth. Road transportation distinguishes between passenger and freight transport. Passenger transport is split between personal cars, motorcycles and bus; the corresponding passenger-kilometres (pkm) demands are projected following an econometric specification (trend modified by per capita income and short and long-term average

[1] 40+ countries of geographical Europe, not the EU strictly speaking.

[2] With each of the sectors having a different ‘transport intensity’ (average ton-kilometres in the production of one good), the same GDP growth can induce varying shifts in transportation activities depending on its sectoral distribution.

[3] Following ‘Zahavi’s law’, establishing that the daily time spent in transportation is quite stable across time and regions of the world, regardless of the transportation mean—and hence of the distance covered.

fuel price elasticities, with asymmetrical elasticities to price increases and decreases) without explicit modal substitution. The fleet of personal cars is split between 6 car technologies based on exogenous assumptions about vehicle costs and fuel efficiency, O&M expenses, a discount rate and limits to the penetration rates. Car vintages are kept track of. As regards freight, the ton-kilometre (tkm) demand of road freight transport is projected following an econometric specification (trend modified by total GDP and short and long-term fuel price elasticities) without explicit modal choice.

SMP (Sustainable Mobility Project) projects the CO_2 and local pollutants emissions from transportation activities of an 11-zone world every five year up to a 2050 horizon, based on an extended set of exogenous assumptions (mobility, freight transport, modal choices, vehicle characteristics, *etc.*).[4] As in POLES, passenger transport is split between personal cars, motorcycles, bus, rail and air transport. The fleet of personal cars is exogenously split between 6 car technologies, according to a disaggregation different from that of POLES in some ways. Car vintages are kept track of. Buses and trucks are split in 2 size categories, modelled as mere stocks with average characteristics (no vintages). 2-wheelers are also modelled as stocks.

Personal cars

Personal cars, or Light Duty Vehicles (LDVs), are given a comparatively high level of detail in the three source models. IMACLIM explicitly tracks the increase in their stock, and variations of their average fuel efficiency. POLES and SMP both have a vintage approach, with characteristics (fuel efficiency, lifetime, *etc.*) specific to each vintage.

Based on these sources LDV local pollutant emissions are computed in the following steps:

- The projection of aggregate European LDV passenger-kilometres of IMACLIM-R is split between countries and technologies *pro rata* POLES' detail. Some of POLES' technologies are further disaggregated (conventional car between gasoline, diesel and CNG-LPG; hybrid car between gasoline and diesel hybrid) *pro rata* SMP assumptions about their respective market shares.
- Passenger-kilometres are converted in vehicle kilometres using SMP's assumptions of average vehicle occupancy.
- Vehicle sales by vintage are deduced from the resulting stock, based on SMP's assumption about the average lifetime of the successive vintages.
- SMP's vintage-specific gram-per-kilometre (g/km) emission coefficients (some of them reassessed) are applied to the vehicle-kilometres of the corresponding vintage to compute the tons of pollutants emitted every given year.

Note that following SMP the emission coefficients of a given vintage increase as the vintage ages.

Buses

IMACLIM-R tracks the passenger-kilometres of public ground transportation, but does not distinguish road from rail. POLES details bus passenger-kilometres. SMP splits a bus fleet between small and large buses, and provides specific fuel efficiencies, load factors, average kilometrage, *etc*. From these sources the emissions of local pollutant by buses are computed in the following steps:

- POLES' projection of bus pkm is split between small and large buses, then between diesel and gasoline engines, *pro rata* SMP.

[4] The absence of any behavioural assumptions regarding mobility, modal choices, *etc*., make SMP more of a 'scenario building tool' than an actual model in the usual sense.

- The resulting pkm are converted to vehicle-kilometres (vkm) using SMP's assumptions about load factors.
- SMP's g/km emission coefficients are applied to these vkm to obtain emissions in tons of pollutants.

Trucks

Same as buses, trucks are too aggregated in IMACLIM, and the emission projections rely on POLES and SMP only:

POLES projects road tkm, that are split between medium (delivery) and heavy freight trucks, and gasoline and diesel technologies, following SMP.

- POLES' projection of road transportation tkm is split between medium (delivery) and heavy freight trucks, then between diesel and gasoline engines, *pro rata* SMP.
- The resulting tkm are converted to vehicle-kilometres (vkm) using SMP's assumptions about load factors.
- SMP's g/km emission coefficients are applied to these vkm to obtain emissions in tons of pollutants.

2-wheelers

Again, 2-wheelers emissions are computed from POLES and SMP only: the stock of 2-wheelers projected by POLES is crossed with SMP's assumption about average annual kilometrage, and SMP g/km coefficients applied to the resulting vkm to compute emissions.

Lead emissions

Lead slightly differs from the 4 other pollutants in that its emission coefficient is given in gram per litre of leaded gasoline consumed. For all gasoline vehicles, gasoline fuel consumptions are derived from the vkm computed as explained above, based on the average litre per 100 kilometre assumed by SMP. An overall coefficient is then applied to the cumulated gasoline consumption to assess the consumption of leaded gasoline—from which a single coefficient, given by SMP, eventually derives lead emissions.

Questioning SMP's local pollutants estimates

With its primary focus on CO_2 emissions, SMP tracks pollutant emissions as more of a by-product. It consequently uses assumptions that are simplified to the point of becoming questionable. A major source of ambiguity is the generalised use of **gram per kilometre** as the unit of emission factors: such a unit might make sense for policymaking, as it targets both the fuel efficiency and combustion quality of vehicles; but it may not be the most appropriate when exploring technical potentials, as SMP implicitly does. The following paragraphs describe some of the undesired implications of resorting to g/km assumptions.

Time profiles of g/l coefficients

In most instances (countries, motorisations, fuels, vehicles) the g/l coefficients computed from the g/km and fuel economy assumptions massively decrease up to 2025, but slightly increase after that year. The reason is simply because emissions in g/km are assumed to stop decreasing after 2025, whereas fuel economy is assumed to continue improving.

This point is left standing, as it is not an unrealistic result for policies targeting the g/km achievements of vehicles. Anyway the increase is very moderate, and has a marginal effect on aggregate emissions if compared to a stabilisation of g/l emissions.

Advantages of hybrid motorisation

The g/km emission factors of the hybrid motorisation are assumed half those of their fully conventional counterparts—an apparently ad hoc assumption, cf. SMP documentation p.80. Converting all emission factors to g/l (considering the assumptions made in terms of fuel efficiency), this implies that the same litre of gasoline or diesel, when burnt in the thermal engine of a hybrid car, produces a varying proportion of the pollution it releases when burnt in the thermal engine of a fully conventional car. This proportion erratically varies from .2 to 1.3 with the year, the region and the pollutant considered—especially so for diesel.

Amendment: g/km emission factors for hybrid motorisation were re-computed by applying the gram per litre coefficients of the conventional motorisation to the l/km consumptions of hybrid vehicles.

Comparing minibuses and medium freight trucks, buses and heavy freight trucks, 2-wheelers and 3-wheelers

This point is similar to the previous one: SMP assumes that (1) the minibuses and medium freight trucks, (2) the buses and heavy freight trucks, and (3) the 2 and 3-wheelers, have the same g/km emission factors (cf. SMP documentation p.85 and 86). However, the assumptions about their average efficiencies differ, and consequently the matches do not hold when considering g/l emission factors—which can vary by a factor of more than 3 from one category to its assumed equivalent.

Amendment: g/km emission factors for all these vehicle categories were re-computed by applying averaged g/l estimates (from the original SMP assumptions) to each category's fuel efficiency. E.g., for buses and heavy freight trucks: the original unique g/km assumption, crossed with the two different fuel efficiency assumptions, provides two g/l figures; these are averaged to a single value, which is assumed to apply indifferently to both the buses and heavy freight trucks, and can be translated in two different g/km figures considering each vehicle's fuel efficiency.

Consistency of CO and CO_2 emissions factors

Adding up the carbon contents of CO and CO_2 emissions leads to widely varying carbon emissions, for the same fuel, across vehicles, motorisations and regions. The table below gives the example of Africa.

		g per l			g per l
LDV	gasoline	667	LDV	diesel	791
LDV	gasoline hybrid	664	LDV	diesel hybrid	793
MFT	gasoline	704	MFT	diesel	783
HFT	gasoline	716	HFT	diesel	789
Bus	gasoline	749	Bus	diesel	791
Minibus	gasoline	777	Minibus	diesel	786
2-wheeler	gasoline	1223			
3-wheeler	gasoline	922	LDV	cng/lpg	562

Table 1 *Carbon emissions adding up CO and CO_2 carbon contents, Africa*[5]

[5] Cf. file *CO Coefficients gram per litre*.

Note that the density of gasoline is 755 g/l, that of diesel 845 g/l. Note also that the hydrocarbons used to model gasoline and diesel are respectively C_8H_{18} and $C_{12}H_{26}$, which gives an approximate carbon density of 636 and 716 g/l (notwithstanding fuel heterogeneity and impurities).

It is doubtful that so much carbon is taken in from the atmosphere, with CO_2 only 0,035% of dry air. It is much more probable that CO_2 emission factors are derived from the entire carbon content of fuels, in which case there is some double counting of the carbon in the CO and CO_2 emissions reported.

Convergence of OECD Europe and Eastern Europe parameterisation

For cars, the emission factors of new vehicles converge by 2030 only. SMP's hypotheses regarding Eastern Europe are based on a gradual phase-in of the successive European standards. This leads both to (1) in the case of PM and CO, gaps that can increase from one time period to the next between Western and Eastern emission standards (the constraints embodied in the EURO1 to EURO5 sets of standards are not linear) and (2) in the case of PM, gaps that can exceed an order of magnitude. This might be questioned, considering that most of Eastern Europe has now joined the EU, and buys cars that are the same as those sold in Eastern Europe (with perhaps different equipments and options, i.e. particle filter, catalyser, but for how long?)

The convergence is similarly slow for vehicles other than cars. It is less questionable since the emission factors are defined at each period for the entire on-road stock—and not only for the particular vintage of the period.

Eastern cars are supposed to age, emissions-wise, twice as fast as Western cars, regardless of the time period (the factor is constant from 2000 to 2050) : their emission factors increase by 50% (vs 25%) each five years.

The life expectancy of Eastern vintages is greater than that of Western vintages, 20 vs 15 years for the 2000 vintage, still 18.3 vs 15 years in 2050.

Main parameters / potential policy targets

From SMP

Emission factors of new gasoline and diesel LDV, from 2000 to 2050, every 5 year.

Emission factor adjustments as vehicles age, from 2000 to 2050, every 5 year. This is the percent increase of emission coefficients after each 5 year period for a given LDV vintage. It is set at 25% for the OECD, 50% elsewhere, constant through time and vehicle types—with the exception of CNG/LPG and hybrid vehicles, who have half those rates (12,5 and 25% respectively).

Emission factors for on-road vehicles other than cars, re-computed as described above.

LDV stock turnover assumptions (average age of vehicle when retired). It is constant, set to 15 years, for Western cars, decreasing from 20 to 18.3 years for Eastern cars (SMP's assumption is -1% every five year).

Load factors of buses (passengers) and trucks (tons).

Gasoline vs diesel vs CNG-LPG relative market shares (used to disaggregate POLES' 'conventional' technology).

Gasoline vs diesel relative market shares for hybrid vehicles (used to disaggregate POLES' 'hybrid' technology).

Theoretical consumption of new vehicles, by technology (fuel), and the corresponding 'efficiency gap'.

Average kilometrage of two-wheelers.

From POLES

Market shares of 6 vehicle technologies (conventional, hybrid, electric, gas fuel cell, hydrogen fuel cell, themric hydrogene).

Bus pkm and trucks tkm.

Stock of 2-wheelers.

From IMACLIM-R

LDV pkm.

Scenario descriptions

The harmonised IMACLIM-POLES scenarios are projections of the world economy driven by a set of central assumptions regarding:

- Demography (a common exogenous parameter to both models, drawn from the UN 2004 median scenario);
- Labour productivity increases (in IMACLIM-R), drawn from the extensive studies developed by Angus Maddison at the OECD;
- The energy system (in both models), through the evolution of both its primary resources and its technology portfolio, mostly drawn from ENERDATA expertise.

The exogenous assumptions of demographics and labour productivity conditions, together with the fundamental constraints embedded in the energy systems assumptions, strongly determine the growth of the 12 economies depicted. However, endogenous international markets for all goods and especially energy commodities, together with the impact of constrained international financial flows, can significantly affect potential growth.

The emissions estimation method described above was applied to 2 harmonised IMACLIM-POLES projections of the world economy in 10 sectors for 12 regions every year up to 2050. These projections are based on the same set of driving assumptions, but differ by the implementation of contrasted carbon policy scenarios.

A 'reference' (REF) scenario entails a moderate carbon pricing in all world regions, starting at different dates. Europe, who is assumed a leading position, introduces a $5 (year 2001 USD) pricing per ton of carbon in 2005, that linearly increases to $10 in 2010, and then to $30 by 2030; the rest of Annex 1 follows in a toned down manner, introducing a signal of $1 in 2005, climbing to $5 in 2010, and reaching $15 in 2050; all other countries implement a policy linearly increasing from 2010 on to reach the same $15 in 2050. The resulting global emissions are comparable to the A1 scenarios of the SRES up to 2020, tending to align on A2 after that date. The economic growth computed by IMACLIM is indeed in line with that assumed by the A1 scenarios up to 2020 (1.5% average annual growth) but slightly lower after that date (1.3% average annual growth).

A 'factor 4' (F4) scenario envisages an ambitious set of carbon policies that aims at curving global carbon emissions to a level guaranteeing an atmospheric concentration no higher than 450 ppmv.[6] Exogenous studies approximate a global emissions trajectory compatible with the objective. This trajectory is then split between regions by assuming a loose convergence of per capita emission trends. The corresponding effort, for Annex I, is ca. a 66% decrease from 1990 levels in 2050—while total emissions by China or India are only allowed to double. Such extreme levels of abatement are obtained not only through high carbon prices (in the order of $370 per ton of carbon), but also through policy measures assumed to trigger an accelerated turn-over in buildings (allowing a swifter transition to more energy efficient housing), and an increased technical progress on

[6] A 450 ppmv concentration level, defined by the IPCC as some sort of safety threshold, is thus used to approximate the rather political objective of a division by 4 of emissions.

transportation (lower consumptions) and industry equipments. However, this only results in a small growth decrease for Europe, with real European GDP navigating 1 to 2 percentage points only below its REF value across the whole projection. This maintained growth is explained by the compensative decrease in international energy prices (due to a much lower demand), highly beneficial in the case of a strongly dependent Europe.