Investment needs for transport infrastructures along low carbon pathways

Preliminary Paper

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Abstract

Transportation mode choices, distances traveled and resulting CO_2 emissions are influenced by transport infrastructures. The latter will either lock-in transport patterns in high-emitting modes or accompany low-carbon pathways. At the same time, future mobility demand increase requires rapid build-up of new infrastructures and upgrade of existing ones. Here we quantify investments needs for transport infrastructures over time to reach both development and climate objectives in different world regions. We compare investments needs between world regions and analyze the main factors determining investment needs for each region. To do so, we build an ensemble of socio-economic scenarios with the integrated assessment model Imaclim-R combining alternatives on model parameters determining mobility patterns. We estimate the investments consistent with the passengers and freight transportation trends in the scenarios and identify their main determinants. We find that expenditures needed for transport infrastructure are reduced along low-carbon pathways compared to investment levels in baseline scenarios. This result is found both at the global and regional scales and is robust to uncertainties. The main decrease is observed in road and rail sectors. Under ambitious mitigation policies, annual investments needs relative to GDP differ between regions, with highest needs in Russia and Commonwealth of Independent States and in Africa and Middle-East. Rail utilization level and road costs are important determinants of investments in all regions. Our methodology can also be used to question the realism of transport activity pathways constructed with models not accounting for transport infrastructure dynamics in case of investments needs particularly high compared to historical values.

1 Introduction

The transport sector is one of the fastest growing GHG emitting sectors. Since 1970 it has experienced the highest growth of greenhouse gas emissions reaching 7GtCO_2eq in 2010 (IEA, 2012b). Global transport activity represented in 2008 28% of final energy use and 60% of oil consumption (IEA, 2012a). Hence significant reductions in emissions from the transport sector will be necessary as part of any mitigation strategy in order to limit below 2C the global temperature increase. Transport modes provide mobility of goods and passengers using different transports infrastructures (road, rail, bridges, ports, airports, tunnels...). This physical infrastructure network, as defined by Fulmer (2009), have specific economic characteristics : (i) immobile capital with long lifetime (Prud'Homme, 2004), (ii) the 'lumpy' character of investments (Lecocq & Shalizi, 2014) and (iii) increasing returns to scale (Driscoll, 2014). Mode choices and resulting emissions from transport are influenced by transport infrastructure. Infrastructure planning can be a lever for low carbon modal shift not only in developed countries (Henao *et al.*, 2015) but also in emerging ones (Tiwari *et al.*, 2016) (Waddell *et al.*, 2007). On the contrary, transport infrastructure create lock-in on future carbon emissions because of very long lifetimes (Guivarch & Hallegatte, 2011). Therefore, infrastructures can either lock-in transport patterns in high-emitting modes or accompany decarbonization pathways.

At the same time, transport activity will increase for the next decades, especially in developing countries because of population and economic growth driving an increase of mobility per capita (Crozet (2009); Schafer & Victor (2000)). Over the next four decades, global passenger and freight travel is expected to double over 2010 levels (Dulac, 2013). This future mobility demand increase requires rapid build-up of new infrastructure and upgrade of existing infrastructure. Yet, some regions, such as Latin America, have experienced lack of transport infrastructures spending in the last decades (Perrotti (2011); Calderón & Servén (2010)). Annual investments allocated to transport infrastructures are limited according to historical data. The maximum investments share of GDP has been approximately 3% of GDP on the 1995-2015 period for most of the countries (see supplementary material).

Therefore, transportation infrastructure is at the intersection between climate and development issues, and the question of investment needs for transportation infrastructure to realize low-carbon transitions while pursuing development goals worldwide is part of the broader question of financing needs for climate and sustainable development goals.

This article aims at contributing to this question, by quantifying investment needs for transportation infrastructure in low-carbon pathways and analyzing how they differ (or do not differ) from investment needs in high-carbon pathways. Climate policies impacts on infrastructures investments are *a priori* ambiguous and could in some countries exacerbate the investment gap or release tension in other places. For instance, on the one hand, the need for investments in rail infrastructure could be driven up by switching freight from road to rail. But, on the other hand, it could be driven down by decreasing demands for transporting large quantities of coal. (Kennedy & Corfee-Morlot, 2013). To resolve this ambiguity, and disentangle the conditions in which investment needs would be higher or lower in low-carbon pathways compared to high-carbon pathways, or high or low in absolute terms, we follow a modelling approach based on two steps. In the first step, we build an ensemble of socioeconomic scenarios with an integrated assessment model, Imaclim-R. From this ensemble of scenarios, we extract the results in terms of future transportation activity trends, for both passenger and freight, in terms of total activity level as well as mode shares. In the second step, we evaluate *ex-post* the investment needs corresponding to the transportation activity scenarios built at the first step.

Because many uncertain factors may affect both future transportation activity and investment needs, such as evolutions in households' motorization levels and structures or building costs for instance, we follow a "what if..." approach to this quantification, based on ensemble of scenarios building and analysis. Rather than following a prediction ambition, we therefore explore uncertainties at play, assess possible ranges of results and highlight robust results or the main uncertain factors associated with specific results.

At both steps of our modelling approach, we thus consider alternative values for the main uncertain factors that may *a priori* determine results. We conduct a global sensitivity analysis to identify the influence of uncertain factors on investments needs, such that our approach address the question of what determines investment needs along low-carbon pathways rather than answering directly the question of the value of investment needs. Also, the quantification presented here evaluates investment needs, i.e. investments that would be consistent with given transportation activity scenarios with some targeted utilization rates of infrastructures and adequate maintenance of infrastructures. This approach is different to predicting future investment, which may be "too small" or "too large" compared to needed levels, thus creating congestion and leading to deterioration of infrastructure quality in the first case or under-utilization of infrastructure and sunk costs in the other case.

We find that global investments needs in transport infrastructures are decreased in low-carbon scenarios compared to high-carbon pathways. This result is also valid at the regional scale, for five regions (ASIA, Commonwealth of Independent States (CIS), Latin America (LAM), Middle East and Africa (MAF) and OECD) we analyze. Furthermore, it is robust to the uncertainty explored in this analysis. Investment needs reductions concern mainly roads, followed by rail and airports infrastructures. When considered relative to GDP, the global annual investments needs averaged over time are similar between high- and low-carbon pathways.

In low-carbon pathways, investment needs relative to GDP present heterogeneity between regions, with lower needs for OECD and high needs for CIS and MAF and intermediate values for ASIA and LAM. The uncertainty ranges and the main determining factors of the uncertainty also differ between regions. The uncertainty ranges are larger for CIS and MAF, and lower for OECD. Rail utilization rate targeted and road construction costs have determine investments needs in all regions but with contributions to the uncertainty differing in magnitude. Other determinants of investments needs are region specific, with the level of mitigation challenges important for ASIA, the mode shift scenario important for MAF and LAM, and the transportation structure parameters important for OECD.

Our methodology and results contribute to the literature in two ways.

First, we conduct the analysis with the same framework at the global and regional levels, over a long time horizon and for an ensemble of scenarios, including both low-carbon and high-carbon pathways. The existing studies are limited either in the time horizon considered (mostly until 2030), in the geographical scope (either only aggregated at the global scale, or conversely only for one region) or in the scenarios considered (thus limiting the comparison between low- and high-carbon pathways) (see Lefevre *et al.* (2016) for a review). For instance, OECD (2007) evaluate rail and road infrastructures investments needs between 2005 and 2030. Global road construction investment are estimated to be between $220 billion and $290 billion per year, with the majority of investments towards replacing deteriorating paved road stock capital. OECD (2012) update figures on rail with an estimation of $240 billion per year between 2009 and 2030. However the scope of those studies is limited to 'business as usual' scenario. Similarly, Dobbs *et al.* (2013) estimate transport-specific spending (road, rail, airports, and harbors) for construction to be between $23 trillion to $25 trillion in cumulative terms between 2013 and 2030, or $1.3 trillion to $1.4 trillion on an annual basis. However author recognized that figures may be underestimated because of maintenance expenditures needs, new investment required to meet climate challenges and existing infrastructure gaps. Dulac (2013) compare a baseline scenario and a low-carbon scenario - the IEA '4DS' and '2DS' scenarios (IEA, 2012a). The author finds cumulative global investments in construction and maintenance for rail, road and parking infrastructure between 2010 and 2050 equal to US$ 120 trillion for the '4DS' scenario, and to US$ 100 trillion for the '2DS' scenario. Investment needs reductions between the '2DS' and the '4DS' scenarios are mainly due to less new roads and parking facilities. Ó Broin & Guivarch (2016) provide cost evaluation of transport infrastructure development for a high- and a low-carbon scenario, and show investments decrease with climate policy implementation for low, medium and high income countries. However, the sensitivity of this result to uncertainty in socio-economic determinants of transportation patterns are not studied, and thus the robustness of this result cannot be evaluated. A few studies focused on specific regions, for instancePerrotti (2011) for Latin America, Pida (2014) in Lefevre *et al.* (2016) for Africa, Bhattacharyay (2010) for Asia. These studies are limited to investment needs estimates only in the short term (before 2020) and for baseline scenarios.

Therefore, our study extends previous estimates and allows a more systematic comparison between regions and between low- and high-carbon pathways. To ease the comparison between regions, and with historical values, we provide investments needs figures relative to GDP, in addition to estimates in absolute terms as in previous studies.

Second, our methodology allows to analyze in a systematic manner the main uncertain factors that determine the investment needs, which is not possible with only a few estimations but conversely requires a proper sensitivity analysis.

The rest of this article is structured as follows : section 2 details our methodology, section 3 presents our results and section 4 concludes.

2 Methodology

Our methodology proceeds in two steps. In the first step, we build an ensemble of socioeconomic scenarios from which we extract the results in terms of future transportation activity trends, for both passenger and freight, in terms of total activity level as well as mode shares. Subsection 2.1 describes the integrated assessment model Imaclim-R used, as well as the model parameters combinations considered to build the ensemble of scenarios. In the second step, we evaluate *ex-post* the investment needs corresponding to the transportation activity scenarios built at the first step. Subsection 2.2 details the modelling approach used in this step. In the results section, we will analyze the range of results obtained from these two steps. For the analysis, to identify the main uncertain factors that determine results, we will use a global sensitivity analysis. Subsection 2.3 details the method we use for the global sensitivity analysis.

2.1 Constructing an ensemble of socio-economic scenarios to explore the determinants of transportation pathways

To explore a range of future transportation pathways, we constructed an ensemble of socio-economic scenarios. The ensemble of scenarios was built with the Imaclim-R model (Waisman *et al.*, 2013). It is a multi-region and multi-sector model of the world economy that represents the intertwined evolution of technical systems, energy demand behavior and economic growth. It combines a Computable General Equilibrium (CGE) framework with bottom-up sectoral modules in a hybrid and recursive dynamic architecture. Furthermore, it describes growth patterns in second-best worlds with market imperfections, partial uses of production factors and imperfect expectations. The scope of GHG gases represented is restricted to CO_2 emissions from fossil fuel combustion. The main exogenous assumptions are demography and labour productivity growth, the maximum potentials of technologies (renewable, nuclear, carbon capture and storage, electric vehicles. . .), the learning rates decreasing the cost of technologies, fossil fuel reserves, the parameters of the functions representing energy-efficiency in end-uses, the parameters of the functions representing energy-demand behaviors and life-styles (motorization rate, residential space, evolutions in consumption preferences...). An extended description of the model is available at `http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_IMACLIM`. In the landscape of Integrated Assessment Models (IAMs), Imaclim-R can be labeled as a recursive dynamic General Equilibrium Model with a medium variety of low-carbon technologies. Diagnostics of its response to carbon pricing places it as a "low response" model, which means that a given carbon price leads to a relatively low abatement and high cost per abatement compared to other IAMs (Kriegler *et al.*, 2015).

Imaclim-R model includes a representation of passenger and freight transportation. Passenger transportation is disaggregated into four modes: non-motorized, private vehicles, public terrestrial transport and air transport. Freight transportation is disaggregated into three modes: terrestrial transport (including both road and rail), maritime transport and air transport. Imaclim-R represents both the technological and behavioural determinants of transportation trends.

The evolution in passengers transport volume and mode shares result from households maximizing current utility under two constraints – a standard budget constraint and a time budget constraint. The four transport modes are differentiated by their respective costs and speed. Access to the automobile mode among households' choices is determined by the motorization rate, which is related to per capita disposable income in each region, with a variable income elasticity that is a function of income levels. This representation allows capturing two stylized facts about passenger transportation: (1) the shift to faster (and more expensive) modes when households' revenues increase, (2) the rebound effect of distances travelled following energy efficiency improvements. Energy efficiency and alternative fuel use in private vehicles are determined by vehicles stocks turnover and households' purchase decisions of new vehicles: standard vehicles (i.e. those that only consume liquid fuels), hybrid cars (i.e. those that consume both electricity and liquid fuels), and 'electric' vehicles (i.e. those that only consume electricity). Technologies are differentiated by their unitary fuel consumption and their capital costs (endogenously decreasing as a function of the learning-by-doing process). Production possibilities in all sectors are described using a Leontief function with fixed intensity of labour, energy, and other intermediary inputs in the short term (but with a flexible utilization rate of installed production capacities). Thus, 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 the input–output coefficients. The input–output coefficients implicitly capture the spatial organization of the production process (in terms of specialization/concentration of production units) and the constraints imposed on distribution (in terms of distance to the markets and just-in-time processes). Both mechanisms drive the modal breakdown and the intensity of freight transportation. Energy efficiency for freight transportation is not represented through explicit vehicle technologies but is implicitly captured through evolution of the input–output coefficients of the energy requirements for the production of final transportation goods for each mode (water, air, and terrestrial transport). The coefficients are responsive to energy price variations, enabling the incentive for technical progress as a function of market conditions to be captured.

Further details about the representation of the transportation sector and analysis of typical results concerning this sector and its interaction with the rest of the economy can be found in Waisman *et al.* (2013). A comparison of results for passengers transportation from eleven global IAMs, including Imaclim-R, is described in Edelenbosch *et al.* (2016).

Imaclim-R is disaggregated into 12 regions (United-States, Canada, Europe, Pacific-OECD, Commonwealth of Independent States, China, India, Brazil, Middle-East, Africa, Rest of Asia, Rest of Central and Latin America). The results in this report will be aggregated at the global level, or into 5 regions: OECD, CIS, MAF, ASIA and LAM. The regions definitions are summarised in the table 1.

Region	Definitions
OECD	United States, Canada, Europe, Pacific-OECD
ASIA	China, India, Rest of Asia
MAF	Middle-East, Africa
CIS	Commonwealth of Independent States
LAM	Brazil, Rest of Central and Latin America

Table 1: Description of regions used for the analysis

To explore the multi-dimensional space spanned by uncertain model input, we followed a method previously developed in (Rozenberg *et al.*, 2014). We first identified the model parameters that can have an impact *a*

priori on scenario outcomes in terms of passengers and freight transportation pathways in particular. The model parameters are then grouped into seven parameter sets presented in Table 3. For each parameter set, two or three alternatives were built with contrasting parameter values. Two groups of parameters correspond to model parameters that determine economic growth, energy supply and demand and energy efficiency in all sectors except the transport specific parameters. These two groups were chosen to relate to the Shared Socioeconomic Pathways (SSP) framework (O'Neill *et al.*, 2017). They match the model parameters used to reproduce the SSP1 "Sustainability", SSP2 "Middle-of-the-Road" and SSP3 "Regional Rivalry" as in Marangoni *et al.* (2017a). Here our set of parameters "demography and productivity" gathers the parameters from the factors population (POP), gross domestic product (GDP) per capita (GDPPC) from Marangoni *et al.* (2017a). We consider three alternatives corresponding to SSP1, SSP2 or SSP3 values. Our set of parameters "determinants of mitigation challenge" gathers the factors energy intensity improvements (END), fossil fuel availability (FF) and low-carbon energy technology development (LC) from (Marangoni *et al.*, 2017b) , except the transport specific parameters. We consider only two alternatives: low mitigation challenges (parameters at their SSP1 values) and high mitigation challenges (parameters at their SSP3 values). Four groups of parameters are transport specific. The parameters are gathered in four groups using the ASIF decomposition (Schipper, 1995) depending on their a priori impact on (1) the Affluence, or volume of transport activity, (2) the Structure of transport, i.e. modes shares evolutions, (3) the Intensity, i.e. the energy efficiency of transport modes, (3) the Fuels, i.e. the deployment of alternative fuels in the transport sector. For each group of parameters, we build two alternatives.
The description of the parameters in each set and their respective values are given in the Supplementary Material.

Sets of parameters (each set may include dozens of technical parameters)		**Alternatives** (qualitative description – see appendix for parameter values)	**Parameter names** (used for the sensitivity analysis in the section 3.3)
Demography and productivity		3 alternatives: SSP1, SSP2 or SSP3	Growth drivers
Determinants of mitigation challenge (fossil fuels reserves and markets, energy demand, low carbon technologies[1])		2 alternatives: low challenges or high challenges	Mitigation challenges
Transport sectors parameters	Affluence (volume of passenger and freight transport)	2 alternatives: low transport demand or high transport demand	Transport activity
	Structure (modes shares)	2 alternatives: individual mobility dominated evolution or shared-mobility oriented evolution	Transport structure
	Intensity (energy efficiency)	2 alternatives: low energy efficiency or high energy efficiency	Transport intensity
	Fuel (alternative fuels)	2 alternatives: low availability of alternative fuels or high availability	Transport fuel

Table 2: Description of parameter alternatives

The combinations of these alternative assumptions generated 96 baseline scenarios, i.e. scenarios with no climate policy implemented. In addition, in each of these 96 "future worlds", we implemented two types of mitigation policies, such that the ensemble of scenarios contains in total 288 scenarios. Both types of mitigation policies are represented through a constraint on the global CO_2 emission trajectory that the model respects with an endogenous uniform carbon price. The two policy cases, 'High mitigation ambitions'[1] and 'Low mitigation ambitions'[2], differ by the stringency of the emissions constraint. The two mitigation scenarios will be designated

[1]The case of "High mitigation ambitions" corresponds to an emission pathway between RCP 2.6(Vuuren *et al.*, 2011) and RCP 4.5. CO_2 cumulative emissions from 1870 to 2100 are equal to 3800GtCO_2. This is between (i) the 3300GTCO_2 value associated with the probability of 33% to not exceed 2°C and (ii) the 4200 GtCO_2 value associated with the probability of 66% to not exceed 3°C (Pachauri *et al.*, 2014). We do not consider the more stringent constraint of an emission pathway following RCP2.6, because with such constraint a large number of scenarios were "not feasible" (see footnote 3 below).

[2]The case of "Low mitigation ambitions" corresponds to the RCP4.5 (Thomson *et al.*, 2011) emission pathway. CO_2 cumulative

in the rest of the text as HMA and LMA, respectively.
In the results section, we will consider results over the 2015-2080 time horizon, because some mitigation scenarios are "not feasible"[3] beyond 2080. To be able to consider the whole ensemble of scenarios, we therefore restrict our analysis to 2015-2080.
Even though a large ensemble of scenarios is created through this approach, it should be acknowledged that only a portion of the full uncertainty space is investigated, and that results are conditional to the choices of sets of parameters to vary and of the alternative values tested. Obviously, the impact of an uncertain driver on the results depends on the numerical assumptions behind each state of the driver. This limitation is inherent to our methodology, but cannot be avoided when accounting for uncertainty in a large number of model input parameters. Furthermore, no objective probabilities can be assigned to scenarios because we are in a case of uncertainty, and not in a case of risks where objective probabilities of parameters are known (Grübler & Nakicenovic (2001); Cooke (2015)). The likelihood of any particular scenario would have to be interpreted as subjective, in the Bayesian sense, and conditional to the model structure used and the alternative values tested. Therefore, the distribution of results cannot be interpreted as an objective distribution of probabilities of outcomes (or probabilities in the frequentist sense). In the results section, the mean of the distribution of results will be plotted to ease figures readability, but this mean is to be interpreted as implying a (subjective) equiprobability of all scenarios.
The results of the socioeconomic scenarios, in terms of transportation activity, serve as input to the second step of the methodology that quantifies investment needs consistent with these transportation activity pathways. Next subsection details the method and data used in this second step.

2.2 Quantifying investment needs for transport infrastructure underlying transportation activity scenarios

The methodology consists in an ex-post analysis of given transportation activity scenarios. It accounts for both passengers and freight. The following transport modes are considered: private vehicles, buses, bus rapid transit (BRT), rail, high-speed rail (HSR) and air transport for passengers; trucks and rail for freight. Sea and air freight are not considered because of lack of data. The methodology to compute investment needs for transport infrastructure underlying a given transportation activity scenario proceeds in four steps: (1) compute mode shares scenarios if they are not explicit, or not at the required disaggregation level, in input scenarios; (2) calibrate existing transport infrastructure; (3) calculate new built needs underlying the mobility scenarios; (4) calculate associated costs for transport infrastructure building, upgrade, operation and maintenance. Steps 2 to 4 are partly based on an approach to model expansion of infrastructure relative to scenarios of transportation activity increase presented by Dulac (2013), with modifications and extensions as presented in the following subsections.
The quantification is done at the aggregation level of 5 world regions (OECD, CIS, Africa and Middle-East, Asia, Latin America). Transportation activities from Imaclim-R results are thus aggregated at this 5 regions level to be used as input to the analysis.
We also add the consideration of uncertain factors determining investment needs, by introducing alternative assumptions on the main parameters that play *a priori* a role in the four steps described above.

2.2.1 Mode shares scenarios for passengers and freight

Transportation activity scenarios resulting from Imaclim-R model runs are disaggregated into three modes for passengers (car, air and other terrestrial transportation) and into three models for freight (air, sea and terrestrial transportation). We make further assumptions to have a finer disaggregation of modes, corresponding the the different infrastructure considered: other terrestrial passengers transportation is disaggregated into buses, BRT, rail and HSR; terrestrial freight transportation is disaggregated into rail and trucks. To do so, we calibrate the respective shares to their 2015 values (given in the supplementary material Table 7) and we consider two alternative scenarios for their evolutions in time. In the first case, we consider shares to remain constant over time. In the second case, we assume that they evolve (linearly) towards levels in 2050 taken from existing scenarios that represent modal shift towards lower-carbon modes:

- Bus rapid transit share reaches 5% of bus share (Dulac, 2013);

emissions from 1870 to 2100 are equal to 4600 GtCCO_2 (RCP pathway). Global temperature is projected to increase by a range of 1.7-3.2 °C from 1870 to 2100 with a median value of 2.4 °C (Pachauri *et al.*, 2014).

[3]We consider here that scenarios are "not feasible" in modelling terms when the endogenous carbon price increase from one year to another required to follow the emissions trajectory is higher than 20%. The scenarios "not feasible" are essentially scenarios with parameters corresponding to the high mitigation challenges alternative.

- Rail freight share is 50% greater than road freight (UIC, 2014), i.e. rail represents 60% of terrestrial freight transportation and trucks represent 40%;
- Rail share reaches 40% of other terrestrial passenger (bus + rail) (IEA, 2012).

Those mode shares targeted are given at the global in the corresponding reports. We applied them in the different regions of our model assuming a convergence of all regions. Mode shares are assumed to be constant after 2050.

2.2.2 Calibration of existing transport infrastructure capacity

We consider the following types of transport infrastructure: (1) roads for passengers private vehicles, buses and freight trucks; (2) BRT specific lanes; (3) Rail tracks for both passengers and freight trains; (4) HSR specific tracks; (5) Airports for passenger activity.
The unit of measure chosen for road transportation is the paved-lane.km. Following Dulac (2013), five, three and two lines are assigned respectively to highways, primary road network and other roads when complete data on different type of road were available. Otherwise, five and two lines are assigned respectively to highways and the rest of the road network. BRT infrastructure is technically considered to be a part of roadway. However, BRT systems require its own investments and imply high-capacity buses in corridors that use private lanes isolated from the rest of traffic. The unit of measure chosen is the trunk.km. For rail infrastructure, we use the track.km unit to deal with infrastructure capacity. Both urban and non-urban are considered, and aggregated, except for high speed rail infrastructure which is considered separately. Airports are included in this study but are not considered as a stock but as a fixed cost by unit of air passenger travel, following Ó Broin & Guivarch (2016). Values for transport infrastructure capacities calibrated in 2015 for the 5 regions of our model are summarized in the supplementary material Table 8.

2.2.3 New built needs underlying the mobility scenarios

At each time step, the need for new built infrastructure, for each type of transport infrastructure considered, is evaluated as the difference between the existing infrastructure stock and the necessary capacity to have a "desirable" utilization rate of the infrastructure.
First, we aggregate private vehicles, buses and trucks to evaluate the utilization rate of the road infrastructure. To do so, we convert the pkm and tkm to vehicle.kilometers (vkm) and use factors of equivalent road occupancy for the different vehicles. The average payload for a truck is assumed to be 13 tons (IEA, 2009). The average passenger occupancy for a bus used is 20 (Schipper *et al.*, 2010). For car occupancies, we use regional values evolution from Imaclim-R scenarios inputs. The passenger car unit value of road occupancy, which is a unit giving the vehicle equivalent in terms of cars, is supposed to be 2.5 for a truck and 2 for a bus based on values from Adnan (2014).
Then, we define a "desirable" utilization rate of the infrastructure and the speed at which it may be reached from actual utilization rate. The actual utilization rate of roads as reflected in data for distances travelled and infrastructure capacities varies a lot between world regions, from 150 000 vkm/paved lane.km for India to more than 1000 000 vkm/paved lane.km for Latin America (Dulac, 2013). A first possible explanation of this heterogeneity is the traffic structure. For freight activity for example, most of the goods are transported by trucks in Latin America (Schipper *et al.*, 2010) whereas 36% are transported by rail in India (Mc Kinsey, 2010). This mode structure has an influence on road occupancy. A second possible explanation is the quality of infrastructure which is heterogeneous between countries. For instance, the paved road share are 20% in Latin America (Perrotti, 2011) and 54% in India (Government of India, 2012). There is uncertainty on what level of utilization rate can be considered as a "desirable". Indeed, high road utilization rate is source of congestion which is associated with financial costs and welfare losses because of (i) vehicle delay, (ii) increased depreciation of vehicle, (iii) specific accidents caused by congestion and (iv) the negative impact of congestion on the location of economic activities in a town (Bilbao-Ubillos, 2008). We choose to consider the two different levels of 600 000 and 900 000 vkm/paved lane.km for desirable utilization rates. Road utilization rate target of 300 000 vkm/paved lane km has also been tested. However, we assume the lowest utilization rate compared to other countries as in India and China are going to increase because of expected surges in mobility demand from private motorisation. We therefore do not consider this value in our results. We do not consider either levels of desirable utilization rates, similar to current levels in Latin America. The region has experienced lack of investments for the last decades (Perrotti, 2011) (Calderón & Servén, 2010). We therefore do not consider the current road utilization rate as a reasonable long term target, but rather as an indicator of congestion or poor infrastructure quality.

The BRT trunk-km occupancy targeted is assumed to be 120 000 bus vkm per BRT km (Dulac, 2013) with roughly 100 persons per bus. BRT system is on the road as well but needs its own lane so there is no influence on the road occupancy.
For the rail transportation, passenger-kilometres and ton-kilometers are summed together in transport units following UIC (2016), assuming that 1 ton-kilometers is equivalent to 1 passenger-kilometer in terms of occupancy. Current rail occupancy levels range from less than 350 000 pkm and tkm per track-km for Eastern Europe to more than 30 million pkm and tkm in Mexico (Dulac, 2013). This important rail occupancy heterogeneity could be the results of different drivers: infrastructure stocks, operating strategies, etc. High and low values of rail utilization rate (20 and 5 million pkm-tkm/track-km) are tested in our model.
The speed at which the "desirable" utilization rates may be reached from actual utilization rates is supposed to be either 35 (targeted values reached in 2050) or 65 years (targeted value reached in 2080). Evolutions towards targeted utilization rates are supposed linear. At each time step, the combination of the desirable utilization rate and the speed assumptions, and the utilization rate from the previous time step determined the objective infrastructure occupancy targeted.
The ideal infrastructure stock is then calculated, at each time step, as the ratio between transport activity and the objective of infrastructure occupancy. The real infrastructure stock from previous time step is compared to the ideal infrastructure stock. In case of under-utilization (infrastructure stock greater than ideal infrastructure stock), new built is not necessary and the occupancy rate can increase. In case of over-utilization (infrastructure stock smaller than ideal infrastructure stock), new built is needed. The calculated need for new built is then confronted to the maximum density of infrastructure in the region and reduced if the maximum would be exceeded. Rail and road density limits applied are based on values from Dulac (2013) (given in the supplementary material Table 10).
For airports, the needs for news construction are not calculated 'physically' because of lack of data for the airports stock and the constraints on infrastructure capacity. It is assumed that passenger activity is the unique driving force for airport building.

2.2.4 Costs associated with new built, upgrade, reconstruction and maintenance

The assumptions on infrastructure unit costs are mainly from Dulac (2013) and represent the yearly investments per unit of infrastructure capacity. For road investments, the costs are split into three categories: new built, upgrade/reconstruction and operation and maintenance. Upgrade and reconstruction are less expensive than new construction because it involves work on existing infrastructure. It is assumed road infrastructure requires reconstruction or upgrade every 20 years. Operation and maintenance costs represent 3% of capital cost and are needed every 4 years (or 0.0075% each year). For rail investments, only new built costs and operation/maintenance costs are considered.
For BRT investments, reconstruction cost shares are assumed to be half of BRT capital development costs. Infrastructure lifetime is supposed to be 20 years as well.
Airports costs are separated into two categories for new built and for maintaining the stock. The price for new built is used for additional passenger.kilometre and the price for maintaining the stock is used for total passenger.kilometre. Because of lack of data, we use values from OECD countries for all regions.
Infrastructure costs in the different regions are summarized in the supplementary material Table 9.
Three different assumptions for costs evolution over time are considered in this study: constancy over time, increase of 50% in 2100 corresponding to 2015 levels and decrease of 50% in 2100. The increase and decrease of costs are supposed to be linear until 2100. Increase of infrastructure costs over time represents the case where, with infrastructure network development or over time, the construction costs (including materials and labor costs) increase or the marginal infrastructure becomes more complex and thus costly. Decrease of infrastructure costs over time represents the case where learning-by-doing progress is a dominating effect.

Uncertain factors	Option 1	Option 2	Option 3	Parameter names
Transport mode shares	Constant	Modal shift		Modal shift
Target of road utilization rate (vkm/paved lane.km)	600 000	900 000		Road target
Target of rail utilization rate (10^6 pkm+tkm/track.km)	5	30		Rail target
Delays to reach targeted utilization rates (years)	35	65		Delay
Evolution of unit cost for roads	Increase by 50%	Constant	Decrease by 50%	Road costs
Evolution of unit cost for rail	Increase by 50%	Constant	Decrease by 50%	Rail costs

Table 3: Summary of uncertain factors considered for investments analysis

To explore the uncertainty space, we combine all alternative options considered for the six uncertain factors, as summarized in Table 3. Therefore, for each transportation activity scenario, we evaluate 144 investment needs quantifications. Doing the quantification for all 288 transportation activity scenarios coming from previous step, we built a database of 144*288 (41472) investment needs quantifications. The limitations of the methodology of building an ensemble of scenarios are the same as those already described in previous section. Furthermore, it may be noted that we consider all combinations of parameters of the investment analysis together with all socio-economic worlds considered: the sets of parameters are varied independently from each other, which neglects the possible cross-correlation of some of the sets of parameters. Neglecting such cross-correlations tends to produce a range of results that is too broad, because some scenarios in the set may not be internally consistent. At the same time, insisting on consistency in scenarios may reduce the ability to identify plausible surprising futures. We therefore will consider the full ensemble of scenarios produced in the analysis.

2.3 Global sensitivity analysis to identify the main determinants of investments needs

In order to identify the main determinants of the investments needs, we conduct a global sensitivity analysis. Our chosen output metrics for this analysis are total infrastructures costs and annual investments needs relative to GDP (averaged over time). The inputs are the parameters or group of parameters described in Tables 2 and 3. We choose to not use the so-called "One At a Time" sensitivity analysis design, where each input is varied while fixing the others. Although widely used by modelers, its shortcomings are largely described in the statistical literature (Saltelli & Annoni, 2010). An alternative approach is the Standard Regression Coefficients Approach (SRC), used for instance by Pye *et al.* (2015) to do a sensitivity analysis for an energy system model. According to the authors, the advantages of this metric are the lack of complexity of their calculation and their independence of the units or scale of the inputs and outputs being analyzed. however, the SRC approach is ill-suited to our model, because it based on a linear relationship between the output and the inputs (Iooss & Lemaître, 2015), while the coefficient of determination R2 allows us to invalidate the linear hypothesis with values obtained lower than 0.8 in our case.
We therefore choose an approach that is more complex, but does not require a linear hypothesis: the methodology based on variance decomposition proposed by Sobol(2001) and described by Saltelli *et al.* (2008). The main advantage of this method is that it is robust to both non-linear and non-monotonic relationships between model inputs and outputs (Iooss & Lemaître, 2015). The portion of total variances is attributed to individual input as well as to interactions between those factors. First-order effect indices represent output variance attributable to each input without considering interactions with other inputs. Total effect indices represent the total contribution to output variance by each input, including interactions with all other inputs. Calculations were done using the python package SALib (available at github.com/SALib/SALib). We chose to display results with radial convergence diagrams, which are drawn using R DataVisSpecialPlots (available at https://github.com/calvinwhealton/DataVisSpecialPlots).

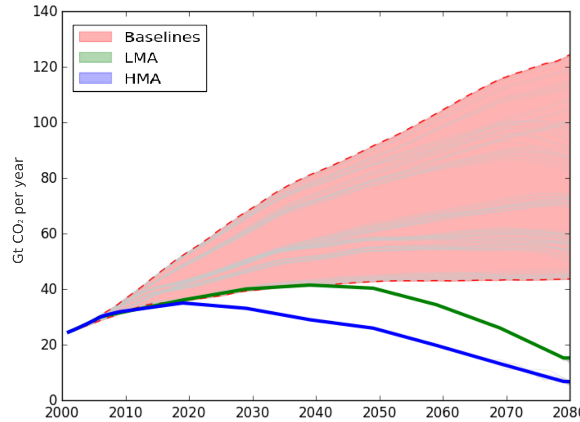
3 Results

3.1 Socio-economic scenarios and transportation pathways

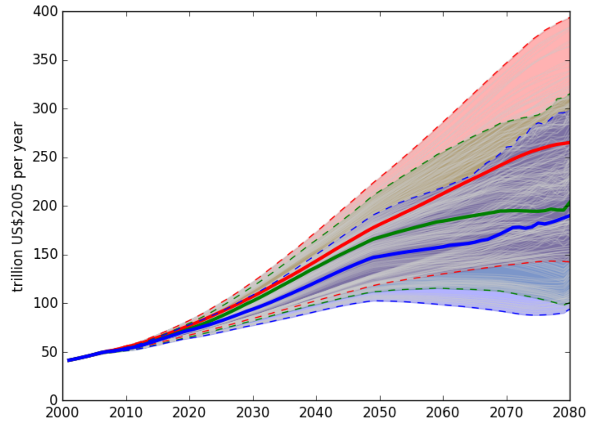
The 96 baseline scenarios results range from about 3100 GtCO_2 to about 6300 GtCO_2 in terms of cumulative CO_2 emissions from fossil fuel combustion from 2001 to 2080 (Figure 1a). Emissions levels in 2050 range from 1.3 to 3 times 2010 levels. This range is comparable to the range covered by the baseline scenarios in the IPCC AR5 database, in which 2050 emissions vary between 1.1 and 3.1 times 2010 levels. Global GDP reached in 2080 in baseline scenarios range from 2 to 7.5 times its value in 2001 (Figure 1b). This range of results is also comparable to the range covered by baseline scenarios in the IPCC AR5 database, in which global per capita GDP in 2080 ranges from approximately 2.5 to 8 times its 2001 value.

The fossil CO_2 emissions from transportation baseline scenarios reach the range of 11.6-19.4 Gt CO_2 per year in 2050 (Figure 1c) which is comparable with the range of 11-18 Gt CO_2 found by Yeh *et al.* (2017). In contrast to global CO_2 emissions trajectories that are given by construction for all mitigation scenarios with the same ambition, emissions trajectories for the transport sector differ between scenarios in the two groups of mitigation scenarios. The share of efforts in CO_2 emissions mitigation between economic sectors is indeed not always the same and depends on the combination of assumptions made on parameters groups values. For instance, in cases where the parameters are such that low carbon technologies in the power sector have limited potentials and higher costs, less mitigation is done in the power generation sector, which requires more mitigation in other sectors to respect the global constraint on total emissions.

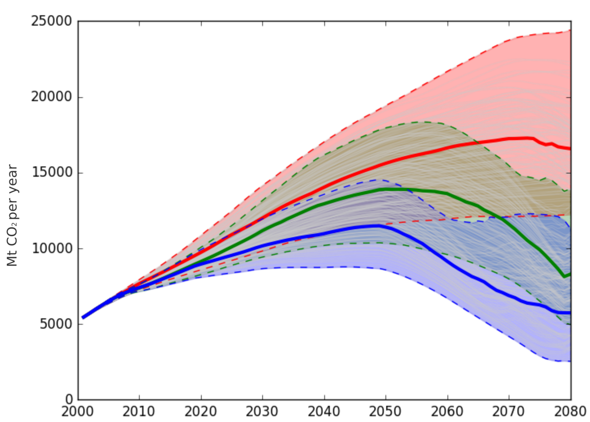
Transportation activity for baseline scenarios reaches in 2080 values in a range from 2 to 4 times the 2001 value for passenger mobility and from 5 to 10 times the 2001 value for freight activity (Figures 1d and 1e). Global passenger mobility is expected to increase by 1.75-2.33 times from 2010 to 2050, ranging from approximately 48 trillion pkm in 2010 to 84-115 trillion pkm in 2050 which is slightly smaller than the range of 1.9-3.3 covered by the baseline scenarios from Yeh *et al.* (2017). Transport activity is reduced in 2080 in low and high mitigation ambitions scenarios compared to baseline scenarios with a median value decrease of respectively 26.4% and 33.2% for passenger mobility and 41.2% and 46.9% for freight activity. Under climate policy,



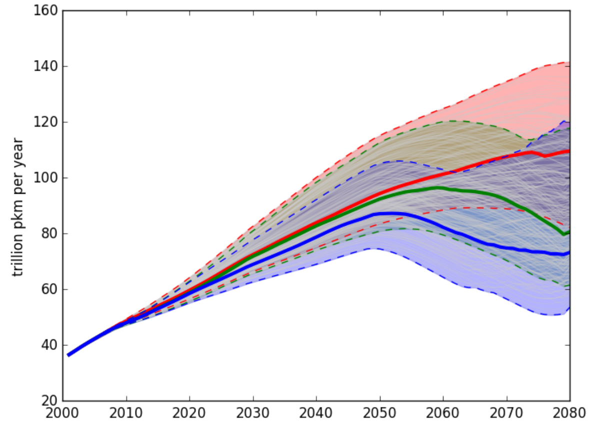
(a) CO_2 emissions from fossil fuel combustion



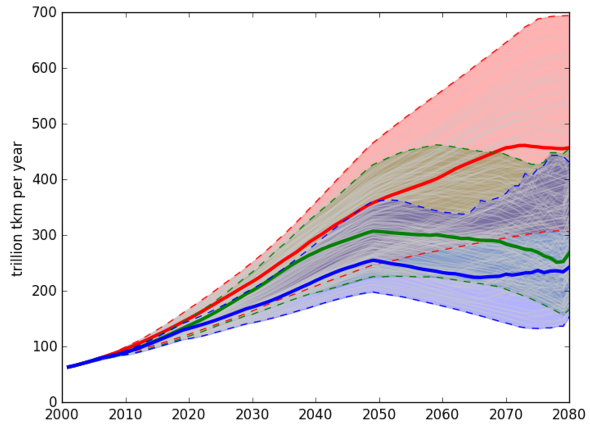
(b) GDP



(c) CO_2 emissions from the transport sector



(d) Passenger transportation activity



(e) Freight transportation activity;

Figure 1: Evolution over time of global socio-economic outputs from Imaclim scenarios; median (solid line) and max/min (dashed lines).

3.2 Effects of low carbon policy on investments

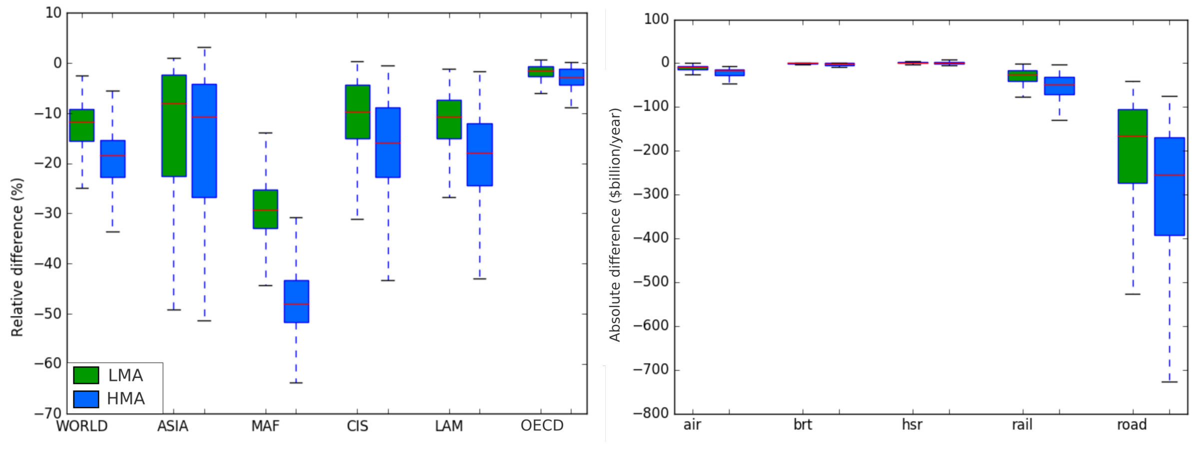
We find for baseline scenarios global investments needs between $1 trillion and $4 trillion per year on average with a median value of $1.9 trillion per year. Those results are comparable with the $2.11 trillion value of Dulac (2013) (whose study includes road, rail, high speed rail and brt infrastructures but not airports), and with Dobbs *et al.* (2013) value of $1.35 trillion per year (including road, rail and airports). Under low carbon policy, we obtained values (i) between 0.92 and 3.4 $trillion per year with a median value of $1.7 trillion for LMA scenarios and (ii) between 0.87 and 3.4 $ trillion per year with a median value of $1.6 trillion for HMA scenarios. The main shares of investments are in road and rail infrastructures with shares between 42 % and 95% and between 2% and 49%, respectively. When considered relative to GDP, the annual investment needs averaged over time are similar for baselines, LMA and HMA scenarios with values between 0.7% and 2.5% of GDP.

For each combination of uncertain parameters, we compute the relative variation in investment needs between each mitigation scenario and the corresponding baseline (*i.e.* the baseline with the same combination of uncertain parameters), for each region and at the global scale (Figure 2a). We confirm the results from past studies (Dulac (2013); Fulton *et al.* (2015) and Ó Broin & Guivarch (2016)) that climate policies lead to a reduction of cumulative spending needs in transport infrastructures. In addition, we add that this effect is robust to the different assumptions on the uncertain parameters considered. The relative decrease in investment needs range from 2% to 25% for LMA scenarios, and from 5% to 33% for HMA scenarios.

Investments needs reduction comes mainly from reduced needs for road, followed by rail and airports : the contribution to total decrease represent respectively more than 40% and 99%, between 0.3% and 45% and between 0.5% and 15%. In the case of HMA scenarios, it translates into an annual decrease of investment needs between 70 and 720$ billion for road, between 5 and 130$ billion for rail and between 5 and 40$ billion for aiports (figure 2b).

This result, of investment needs decreased in mitigation scenarios, is also valid at the regional scale for most of the scenarios but with different magnitudes (Figure 2a). Investments in MAF under ambitious mitigation policy are reduced by [35%-65%] whereas in OECD the variation is lower than 10%. In a few cases for ASIA, investments needs are more important under climate policies with a maximum increase of 3%. 83% of those cases are associated with the assumptions of rail costs increase over time, a high target of road utilization rate and a low energy efficiency in the transport sector.

The overall decrease of investments needs is notably induced by a reduction of transport activity in a low carbon-world according to figures 1d and 1e. The largest decreases in investment needs come from road infrastructures and this effect is amplified for ASIA, CIS and MAF by a mode shift from personal vehicles to low carbon modes (as public transport and non motorized modes) induced by climate policy implementation (see Table 11 in supplementary material).



(a) (b)

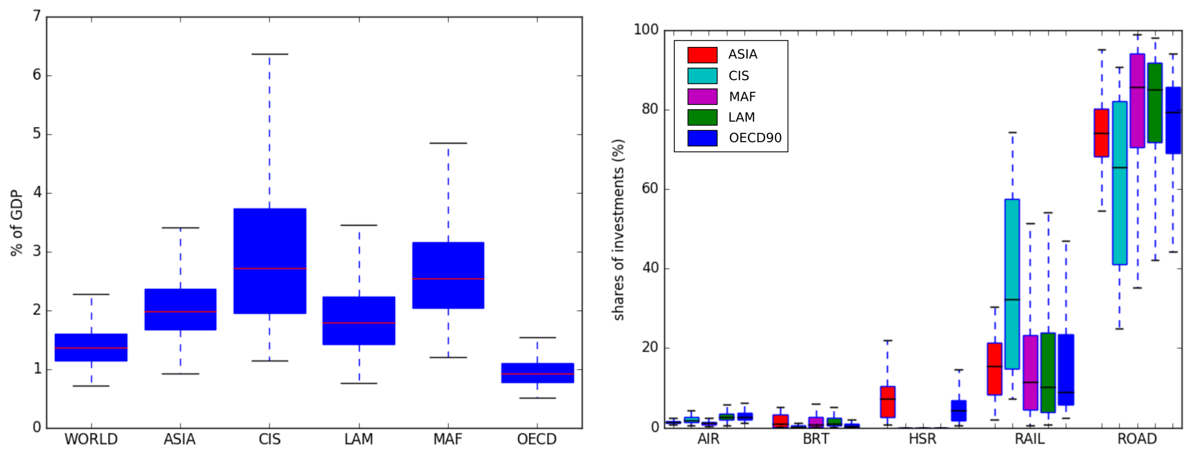
Figure 2: Comparison of cumulative investment needs between mitigation scenarios and their corresponding baselines; (a) : Relative difference of cumulative investment needs (a negative value indicates that the investment is lower in the mitigation scenario); (b) : Contribution of each infrastructure type to total annual investments difference

Even if investment needs are lower in mitigation scenarios compared to baselines, financing these needs may remain a challenge (Granoff *et al.*, 2016). We therefore analyze regional investments needs in low carbon pathways on the following section in order to identify cases of high and low investments needs and their main determinants.

3.3 Regional investments under mitigation scenarios and their determinants

We focus the analysis in this subsection on HMA scenarios, because we want to explore the investment needs in low-carbon pathways and understand their main determining factor. To be able to compare results between regions and with historical data, we quantify the investments needs relative to GDP, and average the results over the 2015-2080 period, in each HMA scenario. Figure 3a shows the distributions of results differ between regions. Median values are the lowest for OECD at 0.92%, and the highest for MAF and CIS, with values of 2.5% and 2.7% respectively. Values for ASIA and LAM lie in between, with median values equal to 2% and 1.8% respectively. The uncertainty ranges of results are specific to each region as well. While expenditures needs are under 2% for OECD in all cases, uncertainty ranges are the highest for MAF and CIS where values range from 1.2% to 9% and 1.1% to 7.1% respectively. Over the period 1995-2015, most countries allocated to transport infrastructures a maximum of 3% of GDP annually, with China being the exception with a maximum of 5% of GDP (see supplementary material). The investment needs we obtain appear to be high in comparison with past values for CIS and MAF for the highest part of the results distribution and for ASIA and LAM in few cases. .

These differences between regions in the level of investments needs can be partly explained by regional characteristics of the transportation sector, summarized in Table 3. Transport intensity of GDP varies between regions and reflects their economic structure, the freight intensity depending mainly on both per capita income and the service sector share of GDP (ITF, 2015). CIS has the specificity of combining high initial rail utilisation level and a freight activity relying mainly on rail infrastructures with a mode share close to 90% (supplementary material, Table 7). Moreover, its freight intensity of GDP is more than twice other regions values. This combination leads to high investments needs, and a share allocated to rail infrastructures more important than in other regions (Figure 3b). Investment needs are important in MAF as well but explaining factors in its transport structure differ. The region has a high passenger intensity of GDP. Moreover, MAF combines high initial road occupancy and a road-oriented transportation system with road shares equal to 88% for land freight and 94% for terrestrial public transport (see supplementary material Table 7). This combination leads to higher and more road-oriented investment needs (Figure 3b). High investment needs could have been expected in Latin America - the region with the highest initial road utilization rate - but low land freight intensity compensates this effect. Results for OECD can be explained by relatively low values for both freight and passenger intensity of GDP.



(a) (b)

Figure 3: Comparison of investments needs between regions for HMA scenarios; (a) : Distribution of annual investments needs relative to GDP (average on 2015-2080); (b) : Allocation of investments between transport modes.

	ASIA	CIS	MAF	LAM	OECD
Road utilisation rate in 2015 (thousand vkm/lane km)	200	300	900	1500	550
Rail utilisation rate in 2015 (thousand pkm+tkm/track km)	20000	25000	10000	6000	6000
Land freight intensity (mean) in 2030/2070 (tkm per US$2005)	0.71/0.65	1.68/1.72	0.71/0.64	0.47/0.38	0.18/0.16
Passenger intensity (mean) in 2030/2070 (pkm per US$2005)	1.36/1.09	0.88/0.7	1.47/0.95	1.08/0.68	0.45/0.27

Table 4: Transport structure characteristics obtained in the model for the five regions considered in this study.

In order to analyze the uncertain factors determining the total variance (or total uncertainty) of results for each region, we conduct a global sensitivity analysis, following Sobol method as described in section 2.3. First, second-order and total-order indices for investments needs relative to GDP are summarized in Figure 4. Results for total cumulative investments as output are given in the supplementary material. We find that the rail utilization rate targeted and the road costs are influencing determinants for all regions. For ASIA, the three parameters influencing the most the results are the road costs evolution, the mitigation challenges and the growth drivers with total indices values equal to 29%[90% confidence interval of 2.5%], 30%[2%] and 17%[1%]. The absence of black lines shows interactions between parameters are limited, the second-order indices being less than 5%. The target of rail utilization rate is the main determinant in CIS with a total-order indice equal to 73%[6%]. This results confirm the importance of rail investments in the total expenditures needs for infrastructures in the region.
Figures 4c and 4d show that determinants are similar for LAM and MAF. Road costs evolution and targets of infrastructures utilization rate (rail and road) determine the most the results of those two regions with values equal to 17%[1%], 34%[3%] and 31%[2%] for MAF and 18%[2%], 27%[2%] and 20%[2%] for LAM. For the modal shift parameter, we quantify first/total order indices are 4%[3%]/13%[1%] for LAM and 4%[3%]/18%[2%] for MAF. The interactions of this parameter with the target of rail utilization rate makes the mode shift assumption influence more total uncertainty than would be apparent in a one-at-a-time sensitivity analysis (figures 4c and 4d). For the OECD region, the main determinants of investments are the road costs evolution, the targets of infrastructures utilization, the growth drivers and the transport structure (figure 4e).

The groups of parameters varied in the Imaclim-R model to construct transport activities pathways have limited influence on the *ex-post* evaluated investment needs, mainly because general equilibrium effects and interactions with other sectors are at play (eg. macroeconomic rebound effect in the case of improved fuel efficiency). Notable exceptions are the growth drivers (especially for ASIA, ALM and OECD regions), the mitigation challenge (for ASIA) and the transport structure (for LAM and OECD). The demography and productivity assumptions considered are such that they lead to higher GDP growth associated with relatively lower transport intensity when growth drivers are as in SSP1, compared to SSP2, and SSP2 compared to SSP3. Therefore investment needs for transport infrastructure relative to GDP are lower in scenarios with SSP1-like growth drivers and higher in scenarios with SSP3-like growth drivers. Higher mitigation challenges lead to higher macroeconomic cost of reaching a given mitigation objective, thus lower GDP, and therefore investment needs relative to GDP are higher. This effect is particularly visible for ASIA, for which mitigation costs increase in the "‘high mitigation challenges"’ cases. The assumption on transport structure parameters induces slower increase of passenger.kilometers traveled in the case of a shared-mobility oriented structure, therefore reducing investment needs for roads. This reduction has a sizable effect on overall investment needs for Latin America (a region that has very high roads utilization rates at the beginning of the period), and for OECD but only when combined with low road utilization rates targeted for this region.
The road costs is an influencing parameter in all regions. This result could be expected because road investments represent the main share of investments needs (figure 3b). A price change on road infrastructure therefore leads to a significant variation in total investment costs. Research and development policy focused on less expensive road construction technologies could be relevant for investments abatement.
The influence for all regions of the rail utilization rate target should however be qualified to the extent that it results from the choice of the two alternative values for this parameter considered here. The result is indeed influenced by the difference between the two values, the high target being 6 times greater than the low target. Moreover, the target of 5000 thousand pkm+tkm/track.km is below all regions initial rail utilization rates (Table 3) and increase as well the importance of this parameter, because it implies investment needs even if transport activity would not increase. In a previous version of this study, we analyzed as well scenarios with a lower target of 300 thousand vkm/lane.km for road occupancy. This value was low compared to 2015 road occupancy levels (Table 3) leading to higher influence of this parameter on results as well. The importance of targeted rail utilization rates for overall investment needs can be interpreted in two ways. A first possible interpretation is the fact that aiming to decrease the rail infrastructure utilization rate may seem unrealistic in

terms of investment needs. This is particularly the case for CIS and MAF regions where investment needs are then higher than actual investments (as a share of GDP) observed in the past. A second interpretation is more policy oriented and identifies the increase of rail utilization rates as a possible lever to reduce investment needs. For regions other than CIS and MAF, optimizing the rail network in order to have higher utilization could thus be an option to avoid high costs pathways.

Similarly, for the targeted road utilization rate parameter, our results highlight the fact that, LAM and MAF having the highest levels in 2015, a reduction in utilization rates leads inevitably to a strong increase of investment needs.

The high influence of mode shift from road to rail for public transport and freight associated with a strong interaction between this parameter and the rail occupancy target in the regions LAM and MAF can be explained by the results summarized in Table 5. For both regions, this mode shift has an opposite effect depending on the rail utilization rate target: it decreases annual investments needs in the cases of high targeted rail occupancy and increases investments needs otherwise. The magnitude of the effect also differs depending on the rail utilization target: the decrease is relatively small whereas the increase is larger (Table 5). Mode shift may be sought for other reasons than CO_2 reductions (for instance, congestion relieve, air quality improvement in cities, etc.). However, it can be a lever to reduce transport infrastructure investment needs only if combined with actions to increase rail infrastructure utilization rates. Otherwise, there is a risk that mode shift leads to greater investment needs.

Scenarios considered	MAF	LAM
Low rail occupancy target + no modal shift	2.6%	1.8%
Low rail occupancy target + modal shift	3.4%	2.4%
High rail occupancy target + no modal shift	2.3%	1.6%
High rail occupancy target + modal shift	2.2%	1.5%

Table 5: Average annual investments needs on the scenarios considered

We obtain important investments needs relative to GDP for some regions compared to historical values and analyse the main determinant of those investments. This analysis shows for instance that the evolution of mobility in CIS does not seem to be compatible with a fall in the occupancy rate of rail for investments of the same order of magnitude as past values. Integrated assessment models (IAMs), as the model Imaclim-R we used, are widely used to explore pathways of decarbonizing the transport sector, producing notably as outputs passenger and freight activity and the economic growth over time. However, most of the models don't take into account transport infrastructures investments in global estimation of costs(Creutzig *et al.*, 2015). Moreover, outputs for the transport sector in future projections as the volume of activity and the mode shares differ between models (Yeh *et al.*, 2017). Our methodology can bring elements to show what those differences mean in terms of investments and question the realism of projections for the transport sector from a financial point of view.

4 Conclusion

In this study, we quantified investments needs of transport infrastructures between 2015 and 2080 along high and low carbon pathways, considering road, rail tracks, brt lanes, high speed rail and airports, at the global level and for five world regions. We constructed transportation activity scenarios using an ensemble of socio-economic scenarios built with Imaclim-R model, an integrated assessment model representing explicitly the transport sector including its non-price determinants and capturing its main interactions with the rest of the economy. We then evaluated *ex-post* the annual investment needs consistent with those transport activity trends.
We found that global cumulative investments needs in transport infrastructures are reduced in low-carbon scenarios compared to high-carbon pathways. We found this result is robust to the different assumptions considered on uncertain parameters influencing transportation pattern and infrastructures expenditures. This result is also valid at the regional level, for the five regions we analyzed. The overall decrease of investments needs is notably induced by a reduction of transport activity in a low carbon-world. The largest decreases in investment are in road infrastructures.
In low-carbon pathways, investment needs relative to GDP present heterogeneity between regions, with lower needs for OECD and high needs for CIS and MAF and intermediate values for ASIA and LAM. The uncertainty ranges and the determining factors of the uncertainty also differ between regions. The uncertainty ranges are larger for CIS and MAF, and lower for OECD. Results for those regions in some cases are particularly high compared to historical values of investments allocated to transport infrastructures for most of the countries. Rail utilization rate targeted and road construction costs determine investments needs in all regions but with contributions to the uncertainty differing in magnitude. Other determinants of investments needs are region specific as the mitigation challenges for ASIA, the transport structure in OECD and the modal shift from road to rail for LAM and MAF. For those regions, we found a strong interaction between the modal shift and the long term rail target, the modal shift tending to increase or decrease investments depending on the rate of rail use targeted.

Inevitably, our results are conditional to the structures of the models we used, and to the alternative values we considered for the groups of uncertain parameters. Therefore, the results cannot be taken literally as definitive quantifications, and could be further investigated with alternative model structures or assumptions. In addition, calibration for initial infrastructures occupancies are based on data collected from different sources, with potentially different completeness and quality levels. If transport activity is underestimated, and/or infrastructure stocks are overestimated, in the data, we may underestimate initial infrastructure utilization rates. This may be the case for ASIA, which has in our data very low initial road utilization. The opposite situation of potential overestimation of utilization rates may also happen, if transport activity is overestimated and/or infrastructure stocks are underestimated. It may be the case for ALM for instance in our data. The lack of data for some regions or the inconsistency between sources call for a serious effort to obtain open and comprehensive data on transport infrastructures.
In our methodology, we do not account for the feedback effect of infrastructure development costs on the economic activity, because we quantify *ex-post* the investments consistent with transportation activity scenarios. The literature has documented a positive relationship with GDP especially in developing countries (Straub, 2008). Accounting for this effect would be a future step in improving the quantifications. An other caveat of our methodology is that we do not include other benefits (other than reducing CO_2 emissions) induced by investments in low carbon transport infrastructures, such as air pollution and congestion reduction. Moreover, the first benefit of low-carbon pathways is the reduction of damages from climate change. Accounting for the latter would have an impact on the evaluations of investment needs. In particular, we anticipate that high-carbon pathways would have higher investment needs because of adaptation costs (Margulis & Narain, 2010), especially in developing countries (Chinowsky *et al.*, 2011). This effect would reinforce our finding that investment needs for transport infrastructure are lower in low-carbon pathways.

Notwithstanding these limitations, our results indicate a robust decrease of investment needs for transport infrastructure in low-carbon pathways. This decrease could compensate additional investment needs along low-carbon pathways in other sectors, as it has been estimated for the energy sector in particular (Gupta *et al.*, 2014). This decrease has thus policy implications in terms of reallocation of investments across sectors, and for climate finance mechanisms implications for policy. In addition, the main uncertain factors determining the investments needs evaluated can be interpreted as possible policy levers to avoid high investment needs and conversely favor low investment needs. Research and development policy focused on low cost road construction technologies and a optimization of rail utilization seem to be potential strategy to consider in this context. Obviously the possibilities to increase rail infrastructure utilization rates will depend strongly on local conditions with respect

to the geography, the structure of passengers travels or the types of goods transported, and the levers to trigger this increase may be of different natures, institutional or technical.
Lastly, our methodology can be used as a sort of 'reality-check' for transportation activity pathways, constructed with models that do not account for potential limitations in annual investments for transport infrastructure. Indeed, the *ex-post* quantification of investments needs consistent with a given transportation activity pathway can question its realism if investment needs would be particularly high in comparison of historical values.

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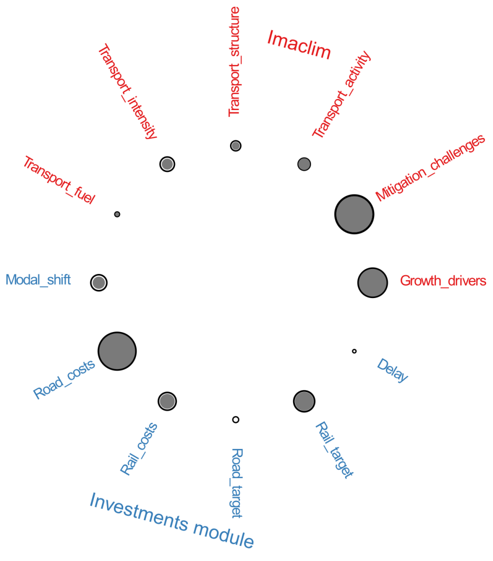
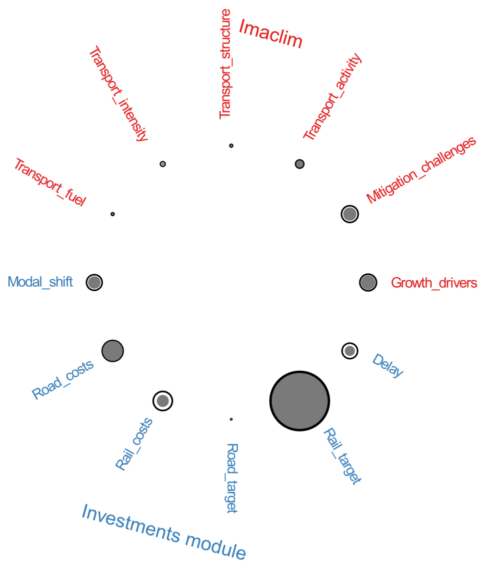


(a) ASIA



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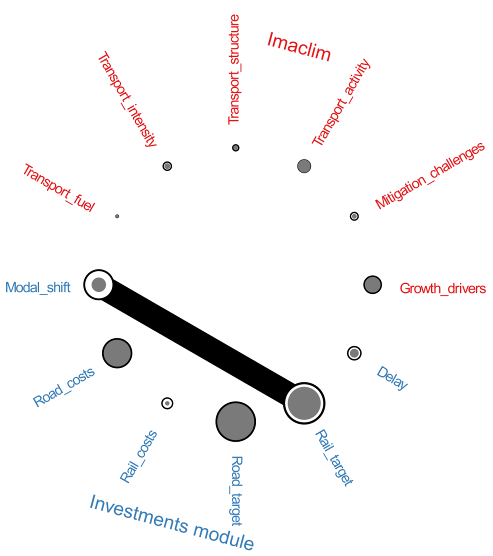

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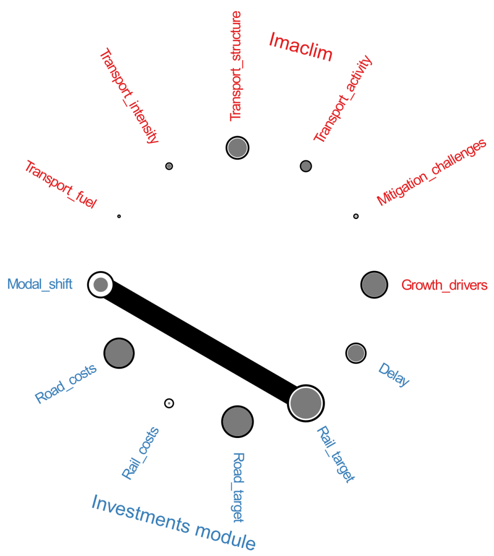

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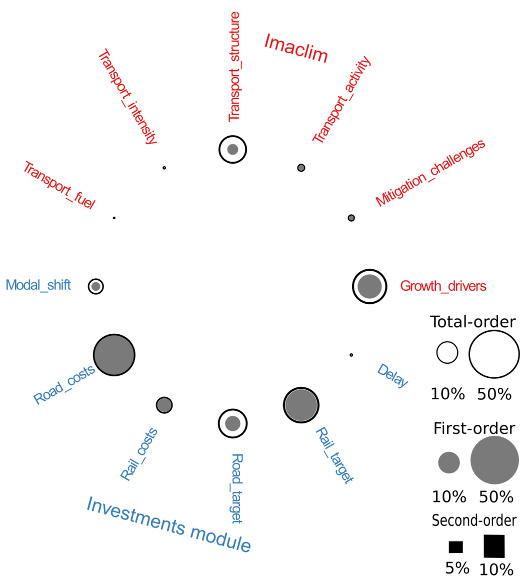

(e) OECD

Figure 4: Sobol method global sensitivity analysis results for each region, for the investments needs relative to GDP. Filled nodes represent the first-order indices and rings the total-order indices. Lines represent second-order indices arising from interactions between inputs. Width of lines indicates the second-order indices. Only the second-order indices greater than 5% of total variance are represented. Parameter descriptions can be found For a description of the parameters, see the last columns of tables 2 and 3.