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ABSTRACT

The rate and manner in which transport infrastructure (e.g. roads, railway tracks, airports) is deployed will play an important role in determining energy demand, greenhouse gas emissions and the economic impact of the transport sector. This paper describes an exercise where the costs of infrastructure deployment for the transport sector have been incorporated into the IMACLIM-R Global E3 IAM, which combines a Computable General Equilibrium Framework with bottom-up sectoral modules in a hybrid and recursive dynamic architecture. In addition to adding these costs, the modelling of the criteria for the deployment of infrastructure for roads has also been improved. It is found that recalibrating the baseline to include costs of and criteria for the deployment of transport infrastructure results in a more accurate baseline as compared to historically observed data for investments in road infrastructure, energy demand and passenger kilometers travelled for the period 2001 and 2013. Regarding macroeconomic effects, it is found that the imposition of a carbon emission trajectory cause GDP to decrease relative to the newly calibrated baseline. However, when the deployment of infrastructure for roads and air travel is further constrained, the GDP loss is less than with a fixed carbon emission trajectory only. This suggests that restricting infrastructure deployment as a complementary policy to carbon pricing to reach a fixed carbon trajectory, lowers the cost of mitigation i.e. the cost premium for a low-carbon energy system can be partially offset by restricting road and air travel infrastructure deployment.

Keywords: Baseline, Integrated Assessment Model, Mitigation, Investment, Policy, Transport, Infrastructure

1. INTRODUCTION

Global greenhouse gas (GHG) emissions from the transport sector have more than doubled since 1971, increasing at a faster rate than any other energy end uses sector to reach 7.0 GtCO2 in 2010. Over three quarters of this increase has come from road vehicles. Direct emissions from the transport sector were about 13.5% of total anthropogenic GHG emissions in 2010 or 22% of total global energyrelated CO_2emissions(Sims et al., 2014). Greenhouse gas mitigation scenarios that keep to 2°C of global warming suggest the need to reduce global emissions to net zero in the second half of this century(Edenhofer et al., 2014).Thus significant reductions in emissions from the transport sector will be necessary as part of any mitigation strategy.

Reducing transport emissions is however a daunting task given the ever increasing demand, the slow turnover of stock and infrastructure[1] and the huge sunk costs in the present transport system (Sims et al., 2014).The authors are highlighting the importance of both the actual transport technology e.g. vehicles and the enabling infrastructure, e.g. roads. Davis et al., (2010)calculate the emissions that will accrue from the use of the existing stock of vehicles (116 $GtCO_2$) and write that the average lifetime for a vehicle in the US is 17 years. Guivarch and Hallegatte, (2011) on the other hand highlight the role of transport infrastructure, writing that transport infrastructure and asset locations create an inertia ontransport emissions, which is larger than the inertia of the vehicles fleet itself. In other words the type of transport infrastructure in place can lock-in the sector to a particular pattern of emissions[2] that will be greater than the emissions from the vehicles calculated by Davis et al., (2010). In their study Guivarch and Hallegatte, (2011)extend the work of Davis et al., (2010) to account for the neglection of the role of transport infrastructure in determining future levels of emissions. Focusing on physical infrastructure for transport and buildings Müller et al., (2013) show that if the per-capita levels of infrastructure enjoyed by people in Western countries was constructed globally using current technologies that this would use up about 35−60% of theremaining carbon budget available until 2050 if the average temperature increase is to be limited to 2 °C. In other words the emissions from the construction of infrastructure are important as well. Globally,at least 25 million kilometres of new roads are anticipated by 2050; a 60% increase in the total length of roads over that in 2010 (Laurance et al., 2014). Thus estimations of future emissions from the transport sector should consider not only, the stock of vehicles but in addition the ‘induced demand’ from the infrastructure and the emissions from the construction of the infrastructure itself.

Waisman et al., (2013) go further than the aforementioned authors by advocating for the consideration of behavioral determinants of transportation, which they write include (1) spatial organization at the urban level, (2) the level of investments in public transport and (3) the logistics organization which determine the transport intensity of production/distribution processes.The authors find that combining transport policies (e.g. dedicated investment in infrastructures for public modes) and a carbon price, can noticeably reduce the level of carbon tax necessary to reach a given climate target relative to a ‘carbon price only’ policy. Waisman et al., (2013) write that to date that E3 IAM modelling of global energy demand had not taken such issues into consideration. This is important because Integrated Assessment Models (IAMs) have become central tools for informing long-term global and regional climate mitigation strategies (EU, 2013), and have evolved to typically incorporate all aggregated sectors of energy end use e.g. transport, industry, buildings and in some cases agriculture and land use change.For energy supply however the lack of inclusion of infrastructure can mean that solar power and natural gas are assumed to develop regardless of the existence or not of power lines. For the transport sector this could mean

[1]The word infrastructure is itself relatively new in linguistic usage and it did not appear as a subject of interest in economics until the 1980’s(Prud’homme, 2005).

[2]For example the construction of the interstate highway in the United States allowed for greater commuting distances and thus the suburban housing developments and the car-dependency that went with this (Lecocq and Shalizi, 2014).

that demand for transport services is modelled to evolve regardless of the existence or not of a road and rail infrastructure.

In addressing greenhouse gas emissions from the energy system,sector focused modelling works and policy discussion documents have traditionally focused on end-uses of energy e.g. heating, lighting, driving and not so much on the enabling physical infrastructure. Notable exceptions to this areDulac, (2013) and Laird et al., (2005). Dulac, (2013) uses results from the IEA Mobility Model (MoMo) to model the infrastructure requirements to support projected road and rail travel through 2050, as identified in the IEA Energy Technology Perspectives 2012 (IEA, 2012). The author finds that net savings in expenditure on infrastructure of USD 50 trillion can be made in an 'avoid-shift' scenario where there is increased use of more sustainable modes of transport. Laird et al., (2005) take a macroeconomic perspective and argue for the inclusion of transport infrastructure in modelling works because its deployment and network effects bring about accessibility, which stimulates development i.e. wages, prices outputs, labor and land markets and can help remove market imperfections.

A stocktaking exercise (Ó Broin and Guivarch, 2015)carried out for the ADVANCE project[3]to assess the level of infrastructure representation in IAMs, revealed that infrastructure modelling to date in IAMs was rudimentary and mostly involves linearly related cost increments for deployed technologies.In five models, REMIND, IMACLIM, IMAGE, MESSAGE and TIAM-UCL, energy transmission and distribution infrastructure e.g. natural gas gridor CCS pipelines are included as individual technologies (McCollum et al., 2013). The IMAGE model(van Ruijven et al., 2011) and REMIND (Pietzcker et al., 2014) also incorporate some network effects. These are that in IMAGE large scale hydrogen use is restricted until the supporting infrastructure has been modelled to exist while in REMIND the quadratic scale-up of an overlay grid is required for the scale-up of VRE. Waisman et al., (2013)as mentioned above, describe the incorporation oftransport infrastructure into the IMACLIM-R Global E3 integrated assessment model, in order to analyze its role in facilitating modal shift or behavioral change towards more sustainable modes of transport. Their model includes road, public transport and air travel infrastructure. It was found that the other models only include the energy supply system for transport e.g. a hydrogen supply infrastructure.

This paper offers a further contribution using the same model as Waisman et al., (2013). Its development on the work of Waisman et al., (2013) is to, (i) incorporate the costs of construction and maintenanceof infrastructure into an IAM, and (ii) develop a more sophisticated approach to how the infrastructure capacity for automobiles evolves. In doing so it incorporates some of the approaches and data ofDulac, (2013)in terms of how to model the deployment of road infrastructure and its respective costs(See Section 2).Results are expected to help address in particular the followingthree questions and so formulate the added benefit of including infrastructure in IAMsand also make policy recommendations regarding transport infrastructure in the context of climate and energy policy.

1. Are the findings of Waisman et al., (2013)still valid when one accounts for the costs of infrastructure?
2. What are the investment costs of different infrastructure pathways?

[3] EU FP7-ADVANCE Project: http://www.fp7-advance.eu/

3. Is the approach to modelling road infrastructure more accurate, as compared to measured data for the period, 2001 to 2013?

To address thesethree questions the work will include the following outputs in its analysis:

- A comparison of modal shares of transport demand from the with and without costs and restrictions on the deployment of transport infrastructure.
- A comparison of GDP development from the model with and without costs and restrictions on the deployment of transport infrastructure.
- A quantification of the cost of transport infrastructure development as compared to GDP.

The paper is organized in standard fashion of introduction – methodology – scenario results, discussion and conclusion.

2. METHODOLOGY

This section describes the development of the model used to analyze the role of infrastructure. The methodology itself involves both model development and scenario implementation.

The IMACLIM-R model used in this exercise is a hybrid dynamic general equilibrium model of the world economy that covers the period 2001–2100 in yearly steps through the recursive iteration of annual static equilibria and dynamic modules. The annual static equilibrium determines the relative prices, wages, labour, value, physical flows, capacity utilization, profit rates, and savings at a year*t* as a result of short-term equilibrium conditions between demand and supply of goods, capital, and labour markets. The dynamic modules are sector-specific reduced forms of technology-rich models, which take the static equilibria at a year*t* as an input,assess the reaction of technical systems to the economic signals, and send new input–output coefficients back to the static model to allow computation of the equilibrium for year*t* + 1. Waisman et al., (2012)describe the architecture of the IMACLIM-R model in more detail[4].

Transport infrastructure in the IMACLIM-R Global model is represented by a variable called *Captransport* and as the name suggests it represents the available transport capacity for various modes. *Captransport* combines three vectors of transport modes (air, public, road) per IMACLIM global region into a matrix. In the model approach it is assumed that public transport (bus plus rail,) has a separate infrastructure to road infrastructure. Infrastructure for freight transport is not considered. The units of *Captransport* are passenger kilometers (*pkm*). For air, although the primary infrastructure needed are airports and runways, for modelling purposes this is also grouped as a generic air transport capacity that is also measured in pkm's. In the model to date (pre April 2015) the *Captransport*values of *pkm* were initialized for the year 2001 (calibration year of the IMACLIM model) by assuming that the capacity of each mode is twice the respective measured *pkm's*.For example, for the Europe plus Turkey region 200 Billion pkm's of air transport were calibrated as being flown in 2001. Thus the capacity of air transport for this region in 2001 is assumed to be 400 Billion pkm. For subsequent model years (2002 to 2100) the *Captransport* variable evolved at the same rate as the changing demand for transport services in the case of public and air transport and the changing stock of vehicles in the case of automobile infrastructure. This can be

[4] See also the updated description on the ADVANCE project WIKI: https://wiki.ucl.ac.uk/display/ADVIAM/IMACLIM

understood as conforming to a congestion avoidance scenario.In addition to this, the construction and maintenance of infrastructure has happened cost free to date. In other words although varying levels of transport infrastructure were deployed each year, there were no costs assigned to this deployment[5].

The number of *pkm's* per mode per year is calculated as part of the model static equilibrium, whereby a representative household in each model region, maximizes their utility (U_k) under constraints of income and a travel time budget. The first step in this process is the definition of, $S_m^{(0)}$, the minimum needs of mobility for commuting and shopping. The amount of additional mobility, S_m - $S_m^{(0)}$, purchased by the representative household, is a factor of income, levels of congestion, a time budget and the price of alternative goods and services. As income increases the representative household can travel further within mode or by switching mode, within a fixed time budget of 1.1 hours and thus obtain more utility from transport. Equation 1 shows how mobility (S) , for region (k), is the sum of four modal choices, the proportion of each being determined by a region specific elasticity (η) of substitution to the increase in total mobilityand (b) are mode-specific parameters calibrated such that the maximization of utility at calibration year is consistent with observed modal shares.

$$\mathbf{S_{k,mobility}} = \left(\left(\frac{\mathbf{pkm_{k,air}}}{b_{k,air}} \right)^{\eta_k} + \left(\frac{\mathbf{pkm_{k,public}}}{b_{k,public}} \right)^{\eta_k} + \left(\frac{\mathbf{pkm_{k,cars}}}{b_{k,cars}} \right)^{\eta_k} + \left(\frac{\mathbf{pkm_{k,nonmotorized}}}{b_{k,nonmotorized}} \right)^{\eta_k} \right)^{\frac{1}{\eta_k}} \quad (1)$$

The substitution between modes and thus the total pkm travelled in each mode within the time travel budget is constrained by the level of congestion in the supporting infrastructure. As the utilization rate of e.g. roads, increases, congestion increases and speed decreases thus limiting the distance that can be travelled and ultimately the level of utility from transport. This development is shown in Figure 1.

$$\mathbf{U_k}\left(\vec{\mathbf{C}}_\mathbf{k}, \vec{\mathbf{S}}_\mathbf{k}\right) = \left[\prod_{\text{goods } i} \left(\mathbf{C_{k,i}} - bn_{k,i}\right)^{\xi^C_{k,i}} \right] \left(\mathbf{S_{k,mobility}} - bn_{k,mobility}\right)^{\xi^S_{k,j}} \quad (2)$$

The total level of mobility (S_k) is calculated in a trade-off with its cost and the cost of other goods, subject to a regional specific elasticity of utility to the increase in income (ξ) as shown in Equation 2.The steps involved in calcuating the division of income between transport and other services and thus the maximum utility (U_k) occur in one general equilibrium calcuation.

Starting in April 2015 an exercise has been conducted as part of the ADVANCE project (Work package 5.4) in which a new approach to updating the *Captransport* variable has been implemented. This new approach has involved, (i) adding the costs associated with transport infrastructure deployment to the model and (ii) changing the way in which the *Captransport(automobile)* variable evolves. As mentioned previously these two changes are based on an approach presented by Dulac, (2013) for the IEA. Dulac's goal is to model realistic expansion of road infrastructure using a bottom-up approach[6]. The authors

[5] The model assumed a constant level of investment in construction each year but this was not linked to infrastructure deployment. In the model development described, such a link has been established.
[6]Dulac (2013), models the expansion of transport relative to an ex-post evaluation of the increase in passenger service demand (pkm) between 2010 and 2030. In this work however, although the costs and principles of

work has included carrying out an extensive survey to establish average costs for road, and rail construction, upgrade and O&M for various World regions. Dulac's costs are used in this work to provide calibration values for the cost of infrastructure for the model calibration year, 2001. Costs for road infrastructure are made up of new roads and parking spaces, upgrade of existing roads and O&M for existing roads and parking spaces. Costs for construction and O&M of Air infrastructure (airports) have been estimated independently using data from the (OECD, 2015). Table 1 lists the dataset of transport infrastructure costs as applied in this work.

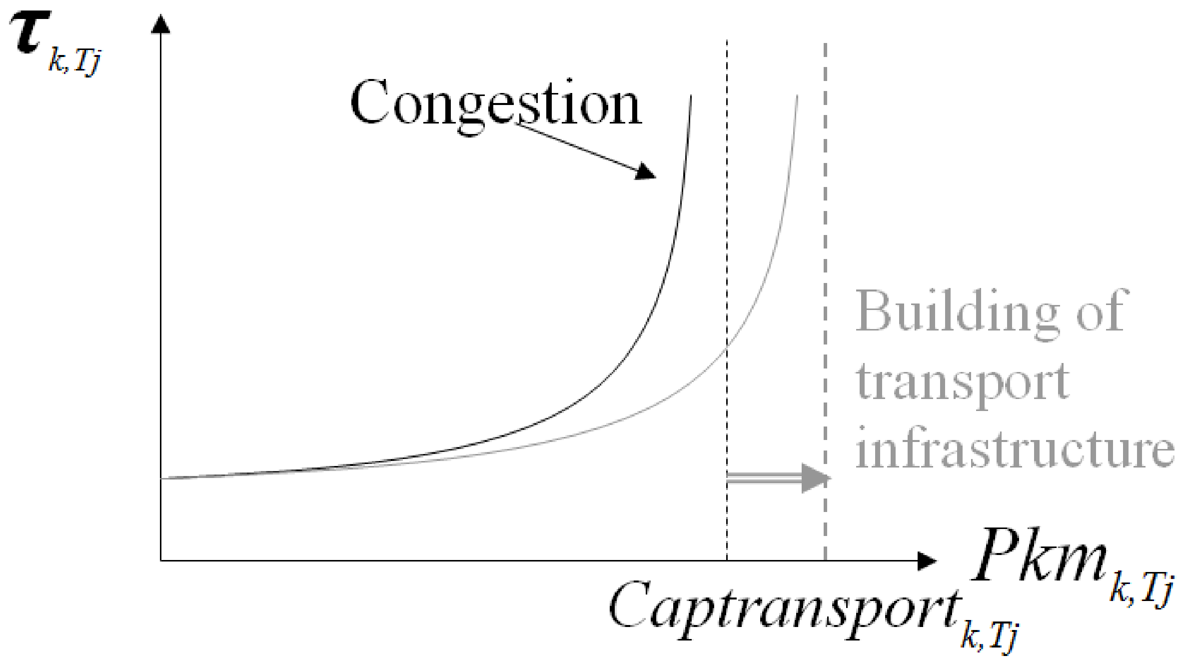

Figure 1 : Marginal efficiency in transport time (the time necessary to travel an additional passenger.kilometer with mode Tj in region k)

In IMACLIM-R costs are made up of price and volume. For the model calibration year (2001) the price of construction (for all sectors) is set to 1 while the volume is a dimensionless unit of construction, equal in absolute value to total investment in construction (infrastructure plus other construction investments). The price, as with the prices of in other sectors, evolves in the IMACLIM-R in response to the macroeconomic components of the model. Because both the prices and the size of the infrastructure evolve, the costs of infrastructure evolve too. Thus while the costs of infrastructure are defined for 2001 (see previous paragraph) they are scaled for each subsequent year by an index which represents the change in prices of the construction sector. For the costs some adjustments were needed. For example the costs for public transport seemed initially to be too high. This was found to be because they are for rail whereas the IMACLIM-R public transport variable also includes bus transport which is relatively cheap. Thus it was decided to multiply the costs for public transport construction by the share of rail in public transport (see parameter 7 in Table 2). It was also assumed that this share increases by 0.5% per

expansion are similar, the model works recursively year on year with attendant feedbacks such as changes in prices of energy.

annum for eight of the twelve IMACLIM-R global regions. The shares for USA, Canada, the EU and Japan were kept static. The notes under Table 2 give more detail on cost calibration issues.

In the new implementation, there is no change in the way *Captransport*is updated for public or air transport. For roads (i.e. used for automobiles but not public transport) the change in *Captransport*occurs due to the following five constraints, of which numbers 3 to 5 are new model developments:

1. The utilization rate of the road network.
2. The change in the stock of vehicles.
3. The construction capacity in the region. See parameter 3 in Table 2.
4. The density of the existing road network. See parameter 5 in Table 2.
5. The maximum percentage of GDP that can go to infrastructure

The first point emphasizes that existing roads may be underutilized and thus an increasing number of vehicles on the road or KM's driven does not necessarily mean that new roads are needed. The second point reflects that an increasing stock of vehicles can lead to increased travel use and pressure to build infrastructure. The third point seeks to incorporate the limits of the construction industry itself i.e. that a ramp-up in levels of construction can only happen if the requisite labor and capital resources, and technical knowhow exist. The fourth point provides a realistic alternative to scenarios of linear growth of infrastructure capacity. In such linear growth scenarios the density of road infrastructure in India can reach the same level as that of Manhattan, New York, by 2050, a clearly implausible outcome(Dulac, 2013). The final point emphasizes the average percentage of GDP that has been spent on infrastructure to date.

The constraints are implemented as follows. It is assumed that each region is striving for a roadway utilization rate of 50% (*UR_automobile_ideal*). Utilization rate in this sense is a modelling construct whereby the number of pkm's travelled is divided by the infrastructure capacity (also measured in pkm's) and measures levels of congestion.50% is chosen as an average between the current high levels of utilization (90%) in Brazil i.e. a high level of road congestion and low levels (15%) in India i.e. a low level of road congestion[7]. The evolution of pkm is anticipated to follow the previous year increase (or decrease) in stock of vehicles and average pkm driven per vehicle. In parallel it is anticipated that the number of *pkm's*driven for each new year (*pkmautomobile_anticip)*changes relative to the annual change in the*stock of vehicles* (itself related to changes in the level of income)and theaverage pkm's driven per vehicle in the previous year. A combination of this anticipated pkm increase and the target utilization rate (as described above) gives the planned *Captransport(automobile)* for the subsequent year as follows:

capautomobile_target=pkmautomobile_anticip/UR_automobile_target (1)

[7] The data on road utilization (Dulac, 2013) are averages for regions, and thus the high levels of congestion in some urban districts should not be confused with these averages.

Table 1 : Infrastructure costs assumed. O&M: Operations and maintenance.

IMACLIM REGION	Road Construction	Road Upgrade	Road O&M	Parking Construction	Parking Upgrade	Parking O&M	Public Transport Construction	Public Transport O&M	Air Construction	Air O&M
USA	1.2	0.2	0.03	300	240	9	0.5	0.05	0.25	0.0025
Canada	1.2	0.2	0.03	300	240	9	0.5	0.05	0.25	0.0025
Europe, Turkey	1.2	0.2	0.03	300	240	9	0.5	0.05	0.25	0.0025
JANZ, Korea	1.3	0.25	0.04	250	200	7.5	0.5	0.05	0.25	0.0025
CIS	1.2	0.2	0.03	250	200	7.5	0.5	0.05	0.25	0.0025
China	1.2	0.2	0.035	150	120	4.5	0.5	0.05	0.25	0.0025
India	1	0.15	0.03	150	120	4.5	0.5	0.05	0.25	0.0025
Brazil	1.1	0.2	0.035	150	120	4.5	0.5	0.05	0.25	0.0025
Middle East	1	0.15	0.03	175	140	3.6	0.5	0.05	0.25	0.0025
Africa	1.2	0.2	0.035	120	95	5.3	0.5	0.05	0.25	0.0025
Rest of Asia	1.1	0.15	0.033	150	120	4.5	0.5	0.05	0.25	0.0025
Rest of Latin America	1.1	0.2	0.035	150	120	4.5	0.5	0.05	0.25	0.0025
Unit	M$US2010/ lane-km	M$US2010/ lane-km	M$US2010/ lane-km	$US2010/ m²	$US2010/ m²	$US2010/ m²	$US2010/ pkm	$US2010/ pkm	$US2010/ pkm	$US2010/ pkm
Notes	1	2	3	4	5	6	7	8	9	10

1. Data in Table 6 (Dulac, 2013) matched to IMACLIM regions
2. Data in Table 6 (Dulac, 2013)matched to IMACLIM regions. Assumed to occur every 20 years.
3. Data in Table 6 (Dulac, 2013)matched to IMACLIM regions. Assumed to occur every 4 years.
4. Data in Table 7 (Dulac, 2013)matched to IMACLIM regions. Assumed to occur every 20 years.
5. Data in Table 7 (Dulac, 2013)matched to IMACLIM regions. Assumed to occur every 3 years.
6. Data in Table 7 (Dulac, 2013)matched to IMACLIM regions
7. First lowest value from Table 13.5 (IEA, 2012) for capital construction per pkm assumed for each IMACLIM region. This assumption is based on the fact that public transport in IMACLIM is for both rail and busses whereas the data obtained is for rail. Note that although the data listed in Table 13.5 of (IEA, 2012) is given in Millions for pkm this is mistaken and the values should be in thousands. The data used is divided in two to reflect that it is for pkms, whereas in IMACLIM the cost of pkm for Captransport is wanted and Captransport for public transport is calibrated in 2001 to be two times the number of pkms.
8. First lowest value from Table 13. 5 (IEA, 2012) for O&M per pkm assumed for each IMACLIM region. This assumption is based on the fact that public transport in IMACLIM is for both rail and busses whereas the data obtained is for rail. Note that although the data listed in Table 13.5 is given in Millions for pkm this is mistaken and the values should be in thousands. The data used is divided in two to reflect that it is for pkms, whereas in IMACLIM the cost of pkm for Captransport is wanted and Captransport for public transport is calibrated in 2001 to be two times the number of pkms.
9. Time series data on investments in airport infrastructure from OECD (http://stats.oecd.org/Index.aspx?DataSetCode=ITF_INV-MTN_DATA) divided by data for air pkms from Schaffer (Schäfer, 2007).
10. Time series data on maintenance in airport infrastructure from OECD (http://stats.oecd.org/Index.aspx?DataSetCode=ITF_INV-MTN_DATA) divided by data for air pkms from Schaffer (Schäfer, 2007).

This result is then compared against the third and fourth constraint listed above : (i) The construction industry capacity in the region(Parameter 2 in Table 2), and (ii) The density of the existing road network(Parameter 3 in Table 2). These are two checks on the amount of new road infrastructure that the model estimates. The construction capacityis assumed to change annually with the increase or decrease in production in the construction sector. Annual production for each sector iscalculated in the static equilibrium (see above) of the model. The density limit is assumed to be constant.A variable *New_road*s is then defined as the difference between *Captransport(automobile)* from the previous year and that calculated according to the aforementioned constraints. *New_roads* is then added to *Captransport(automobile)* from the previous year to update this metric.

A final constraint on *Captransport(automobile)*, the fifth listed above, the amount of investment that can go on infrastructure (*Max_Infra_Road_Invest*), is then introduced. This has initially been set at 2% of the value of GDP in accordance with a recently published ITF report (OECD/ITF, 2015). The report states that road spending has been generally found to decline with the level of GDP per capita. For OECD countries the level is currently around, 1%, while for eastern European and Asian countries it is 2% or higher. A development on this work could be to have a region specific cap that declined as GDP rose, however for the current implementation a global figure of 2% is used. The 2% cap covers the cost associated with road infrastructure (construction, upgrade, O&M and parking spaces). Given the substantial road networks in place in OECD countries upgrade, O&M and parking spaces(Parameter6 in Table 2) can combined make up over 50% of spending on road infrastructure (See**Figure 7**Figure 8for the percentage of GDP spent on infrastructure in the scenarios implemented in this work). Model testing has shown that this constraint also prevents the capacity of road transport rising too fast. Despite the aforementioned constraints this can still occur in the model. This is because the increased capacity modelled for *Captransport* allows greater distances to be travelled (*pkmautomobile*) within the travel time budget (as modelled in the static equilibrium of IMACLIM), and thus *pkmautomobile_anticip* (see above) which is the basis for *capautomobile_target,* can increase rapidly. If it is found that the combined cost of roads, *C_roads*, exceeds 2% of GDP, the variable *New_roads* is recalibrated to be the length of road that would be possible to construct for the difference between 2% of GDP and the combined cost of road O&M, upgrade and parking spaces.

Table 2 : Modelling parameters for road infrastructure in IMACLIM-R Global model.

	Parameter Name	Value	Unit
1	UR_automobile_ideal	50	% pkm/Captransport
2	constr_limit	30 – 355[a]	Lane-km/year in thousands
3	density_limit	1-6[a]	Lane-km per km^2 land
4	conv_pkm_lanekm	4-5 X 10^{-7}	Lane-km/pkm
5	Max_Infra_Road_Invest	2	% of GDP
6	park_space	2X15 – 3X18[a]	Square Metres where 2x means two parking spaces
7	share_rail_OT	5 - 70 [a]	%

[a]Values for model reference year which varies depending on regional circumstances [b]Variable converted to pkm/lane-km using *conv_pkm_lanekm.*

Note that the budget cap does not cover public transport or airports as infrastructure costs for roads make up 70% or more of inland infrastructure investment (OECD/ITF, 2015), but also because doing so would necessitate a decision as to how to allocate budget between road, public transport and air. In an alternative scenario other budget caps on spending for public transport or airports infrastructure could be introduced.

Thus to summarize, Captransport (automobile), increases to ensure that congestion is avoided despite increasing numbers of vehicles and pkm's driven, but within the bounds of a realistic level of construction set by, the construction industries capabilities, the existing road density and the budget available for road infrastructure. Table 2 presents the key modelling parameters involved.

For the baseline scenario GDP, population growth, and active population structure were harmonized to SSP2 projections(Dellink et al., 2015; KC and Lutz, 2014). This is a new development in the IMACLIM model. Previously population growth was based on exogenous projections from the UN. GDP is an endogenous variable in IMACLIM which means that in order to ensure that GDP growth conformed to the SSP2 GDP scenario other parameters such as energy efficiency, fossil fuel resources and labour productivity needed to be adjusted.

The following steps thus summarize the model development.

- **Step 0**: Harmonize baseline population and GDP growth scenarios to SSP2.
- **Step 1**: Add costs for infrastructure deployment as per Table 1.
- **Step 2**: Add additional constraints on deployment
    - The construction capacity in the region i.e. the workforce capability
    - The maximum road density in a region
    - The maximum percentage of GDP that can go to road infrastructure – set to 2%

3. Scenarios of Transport Infrastructure deployment explored

This section presents results from the implementation of the model developments described in the previous section. This first involves the implementation of the following two baseline scenarios in the IMACILM-R Global E3 model:

1. Baseline with no costs for infrastructure or constraints on its deployment (Recalibrated baseline as per Step 0 above)
2. Baseline with costs for infrastructure and constraints on its deployment (Recalibrated baseline plus Steps 1 and 2 above) (BCC)

The idea with these two variants isto isolate the effect of the introduction of costs and constraints on general baseline scenarios i.e. how significant an impact do the introduction of these additions have on the baseline that has heretofore been used. Results from these two alternative baselines are compared with measured data for the period 2001 to 2013, to see which modelling approach results in a more accurate baseline. This is done forthree variables for which measured data is available, total energy demand in the transport sector, total pkm's travelled, and investment in transport infrastructure and maintenance,. The measured data for investment and passenger kilometers was obtained from the

OECD/ITF (OECD, 2015) while the data for energy demand in the transport sector was obtained from the IEA, (2016).

Following this four scenarios with a fixed carbon emission trajectory are run. These scenarios are implemented to investigate the role of a carbon price in isolation and also to see if non-price polices, such as restricted infrastructure expansion could have an effect. Note that restricted infrastructure deployment (RI) in this sense means a further exogenously determined restriction in the deployment of road and air travel infrastructure in addition to the five constraints listed in the methodology. In detailthis involvesthe implementation of the following four fixed carbon trajectory scenarios where the trajectory corresponds to a peaking of global emissions in 2030 and emissions reaching back their 2010 level in 2050:

3. CO_2 emissions follow the fixed carbon emission trajectory with no costs for or constraints on the deployment of infrastructure being included.
4. CO_2 emissions follow the fixed carbon emission trajectory while in addition costs for and constraints on the deployment of infrastructure are included (CO_2 CC).
5. CO_2 emissions follow the fixed carbon emission trajectory while infrastructure deployment for roads and air travel is constrained to 70% of what it was projected to be in Scenario 3.
6. CO_2 emissions follow the fixed carbon emission trajectory while infrastructure deployment for roads and air travel constrained to 70% of what it was projected to be in Scenario 4 (CO_2 CC RI).

The scenarios outlined are summarized in Table 3 where scenarios 1, 3 and 5 are the same scenarios as implemented by Waisman et al., (2013), i.e. pre the current model development, and scenarios 2, 4 and 6 are new.

Table 3 : Scenarios of infrastructure deployment applied in this work.

		Baseline	Mitigation
Default Modelled Infrastructure Deployment	No Costs or constraints	1	3
	Costs and constraints	2	4
Exogenous Limit on Infrastructure deployment for road and air travel	No Costs or constraints	X	5
	Costs and constraints	X	6

The results are divided into two parts that describe(i) Scenarios 1 and 2(alternative baselines)and (ii) Scenarios 3 to 6 (alternative fixed carbon trajectory scenarios) respectively.

3.1 Baseline developments with improved modelling of infrastructure.

Figure 2 shows how the infrastructure in place for transport changes with the inclusion of costs and constraints. Figure 2 shows that the deployment of road infrastructure falls while that for public transport and air travel increases. As less road infrastrucutre is deployed, users switch to public transport and air travel.This is because less road deployment means that congestion on road increases thus decreasing the utility of road travel. The subsequent increase in demand for public transport and air travel results in the infrastructure necessary for these two modes being deployed.The magnitude of the increased demand for public transport and air travel is also helped by the fact that lowered demand for automobile transport lowers demand for oil and this lowers energy prices. Energy prices are a small fraction of total costs for public transport and air travel and thus increase the desirablity of these modes for transport trips. This is a rebound effect which is similar to what is allegedly happening in the USA at the time of writing where lowered gasoline prices are leading to housholders driving more. The empirically measured magnitude of such a rebound effect may however be smaller for falling then for rising energy prices (Hymel and Small, 2015).

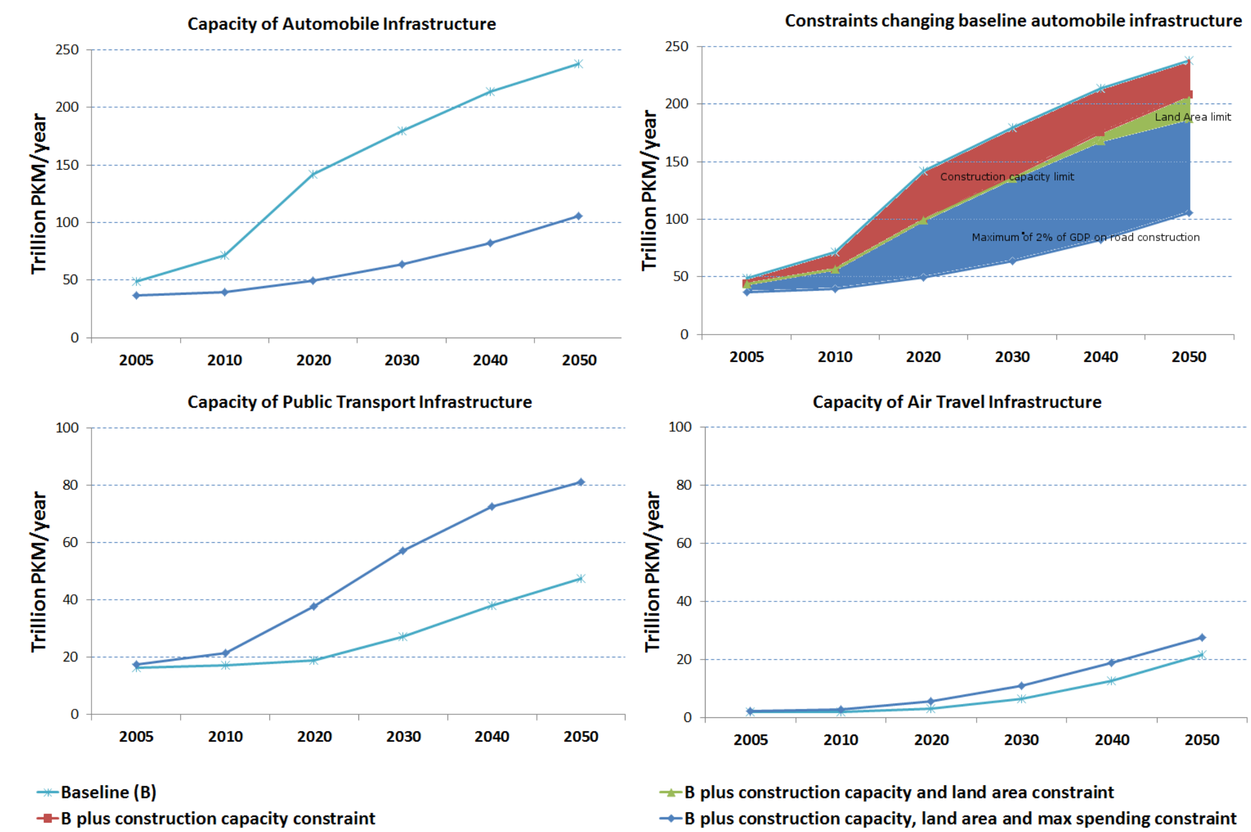

Figure 2 : Transport infrastructure deployment in Baseline Scenarios

The upper-right-hand section of Figure 2 shows the role of constraints 3,4 and 5 (listed in Methodology) in affecting the deployment of road infrastructure. These results for the individual constraints are obtained by running the model for each of the following cases:

1. Baseline plus costs
2. Baseline plus costs and a construction limit
3. Baseline plus costs and a construction and density limit
4. Baseline plus costs and a construction, density, and maximum spending limit

While the construction capacity (Constraint 3 – See Methodology) and maximum spending constraint (Constraint 5) are important from 2020 on the density limit (Constraint 4) only becomes important from 2040 on. For the latter constraint it makes sense that it takes over 40 years for a road infrastructure density limit to be met in a number of regions given the current low current density of road infrastructure.

The deployment of roads for automobiles is over 100% greater in 2050 in the scenario without costs or constraints while that for public transport is over 100% less in the same scenario. This can be seen in the two left hand panels of Figure 2. These are large effects. The question that thus arises is which or the two scenarios are correct?

Estimates for total *pkm* travelled, energy demand for transport andinvestment in roads (in billion US$) are compared to real measured data for these variables. Figure 3 shows the comparison for total PKM travelled and for Energy Demand of Transport Sector. For the latter variable global energy demand for the sector is used while for the former measured data is used for seven regions for which data from 2001 to 2013 was available from the ITF/OECD: USA, Canada, Europe &Turkey, Japan &Korea& Australia &New Zealand, Russia, China and India. In both cases it can be seen that the baseline scenario in which the costs and constraints on the deployment of infrastructure have been included (Baseline (New)) is closer to the measured data.

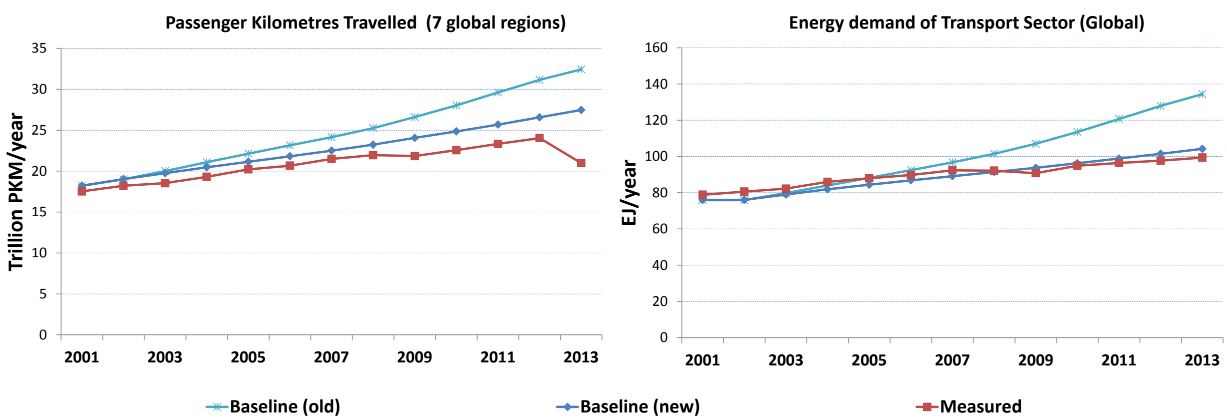

Figure 3 : Comparison of measured with estimated data for PKM and Energy Demand of Transport Sector.

Figure 4 shows average investment in the construction of new roads between 2001 and 2013. This is for the same countries as for which data was available for total PKM travelled except China for which data was not available. Again it can be seen that the baseline scenario in which the costs and constraints on the deployment of infrastructure has been included is closer to the measured data. In this case the model estimation for the original baseline is literally, 'off the chart'.

Given that in all three cases, that the results of the modelled scenarios for the baseline scenario in which the costs and constraints on the deployment of infrastructure have been included are more in accordance with measured data for the period 2001 to 2013, it is assumed that the new baseline is more accurate and thus theresults for the deployment of transport infrastructure shown in navy blue (diamond markers) Figure 2 are an improvement on the original baseline scenario (in sky blue (cross markers) in Figure 2). Hence it can be said that the inclusion of the costs and constraints outlined in the Methodology has improved the baseline.

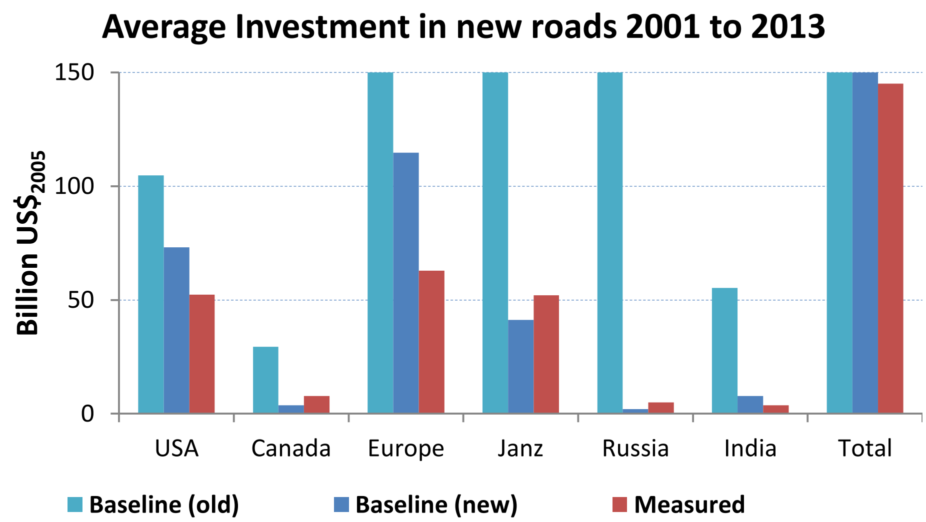

Figure 4 : Comparison of measured with estimated data for average annual investment in new roads.

3.2 Fixed carbon trajectory scenarios with improved modelling of infrastructure.

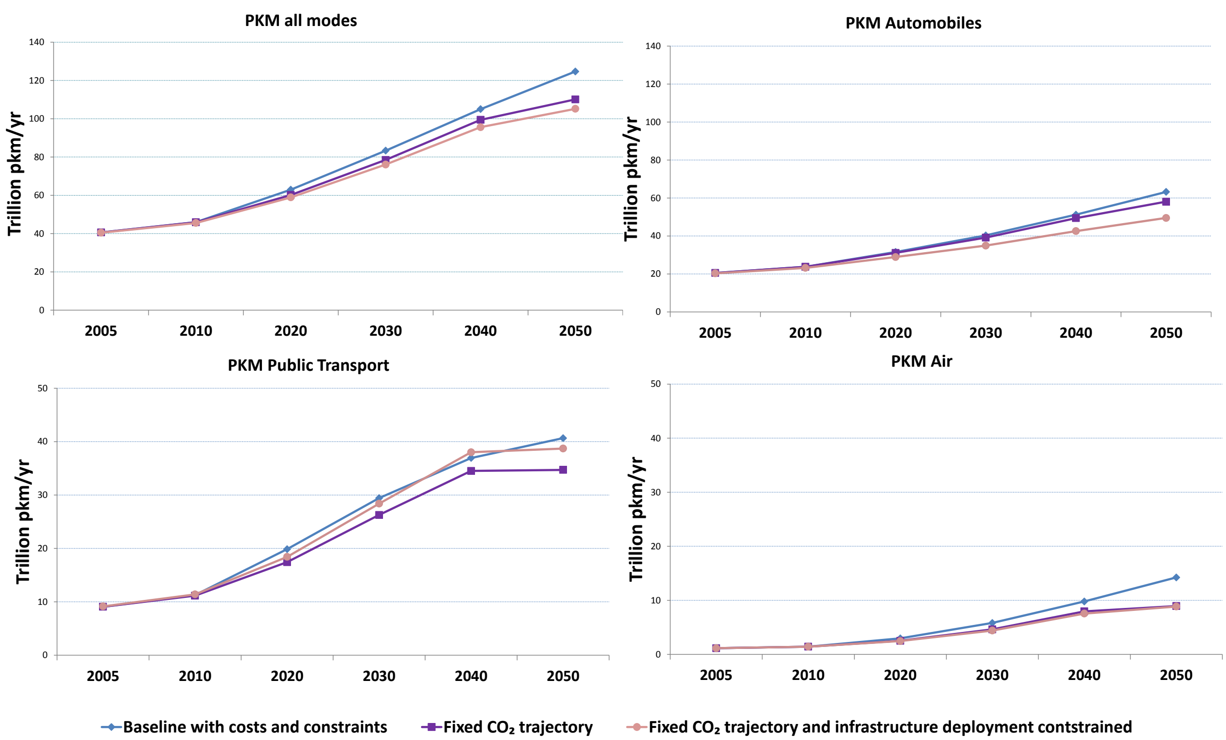

Figure 5 : Passenger Kilometers (PKM's) in new Baseline and under two fixed carbon trajectory scenarios.

Introducing a fixed carbon emission trajectory across the globe changes activity and carbon emissions in the transport sector. Figure 5 shows (purple line – box markers) that pkm's driven falls in all models with the introduction of a fixed carbon trajectory. When an additional constraint on the deployment of road and air travel infrastructure is included (30% reduction on previous scenario) pkm's driven fall further for automobiles and air travel but actually increase for public transport. This can be observed in the pink line (circle markers) in the lower left hand panel of Figure 5. These results follow *a priori* expectations about how demand for the three transport modes would react to limitations on carbon emissions and infrastructure deployment.

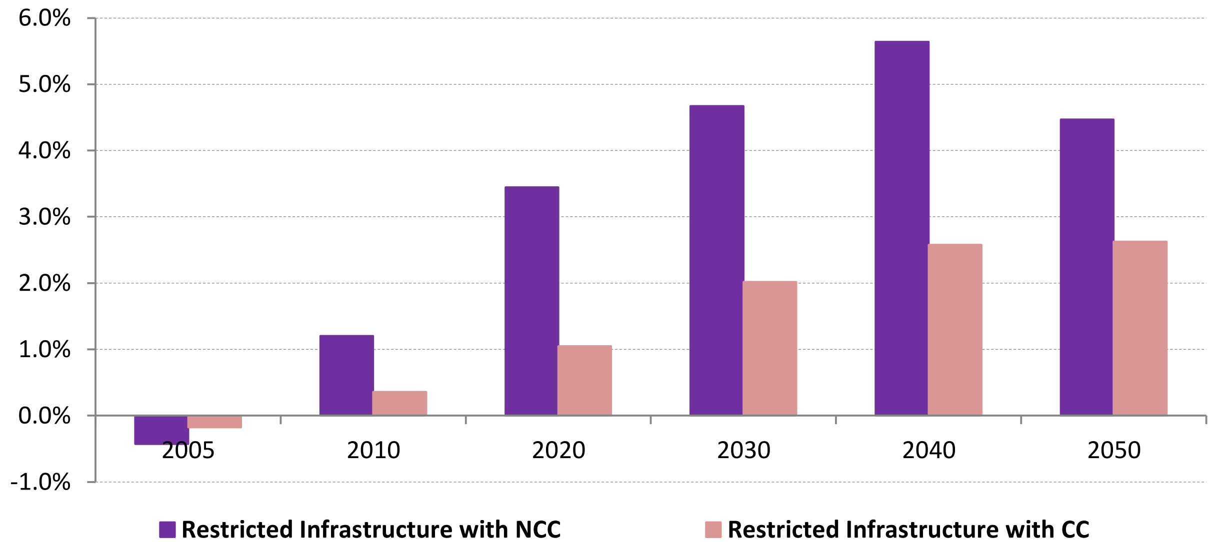

Figure 6 : Reduction of mitigation cost due to restricting the deployment of infrastructure, measured as the relative GDP difference between restriction/non-restriction scenarios. The first bar shows the difference between restriction/non-restriction scenarios without any other costs/constraints on infrastructure deployment (NCC) while the second bar shows the same difference in scenarios that also include costs and constraints on infrastructure deployment (CC).

Restricting carbon emissions to meet a target cause GDP to decrease relative to a baseline[8]. However when the deployment of automobile and air travel infrastructure is also constrained the GDP loss is less than with the fixed carbon emission trajectory only. This suggests that restricting infrastructure deployment is a complementary policy to a fixed carbon trajectory and lowers the cost of mitigation. This is shown in Figure 6. With the carbon trajectory fixed i.e. carbon targets are met, the lowered investment in transport infrastructure, and the relatively lowered oil prices that this results in creates more activity in public transport and air travel (similar to as was described in the previous section for the deployment of infrastructure for public transport and air travel) and also moves investment to more productive sectors. The meassage from this for policymakers is that there is a dividened from restricting infrastructure deployment – a lower cost of mitigation i.e. a better economy. This confirms and improves upon the findings of Waisman et al.,(2013), the difference with that paper being that now that the costs for and the 'real-World' constraints on the deployment of infrastructure are now included. Referring to the scenarios shown in Table 3 what we have shown in Figure 6 is that the GDP gain between scenarios 3

[8] This is a standard results from IAM low-carbon scenarios i.e. there is a cost premium for the deployment of a low-carbon energy system which causes GDP to be lower than in a baseline scenario.

and 5 (what Waisman et al., (2013) studied) and 4 and 6 (what is implemented in this work) have the same sign although differ by a number of percentage points in magnitude. The gain is less once costs and constraints have been added but it is still a gain nenetheless. Seen another way, the cost premium necessary to build a low-carbon energy system can be partially offset by restricting the deployment of infrastruture for road and air travel, thus lowering the overall cost of mitigation. In a scenario with restricted automobile infrastrutucture deployment there would also be less use of automobiles which should lead to better urban air quality (Woodcock et al., 2009). An investigation into the impacts of this is however beyond the scope of the model used.

Figure 7 and Figure 8show the estimated cost of infrastructure deployment and maintenance in absolute terms and as a percentage of GDP for the years 2020 and 2050 respectively. Results are divided between low-, medium- and high-income regions as shown in Table 4. In analyzing results note that the economies of the low-income regions grow a lot over the coming century following the catch-up assumption included in the SSP2 GDP growth scenario(Dellink et al., 2015).

Figure 7 shows that the investment needed in infrastructure increases between 2020 and 2050 in all three scenarios. Comparing the baseline to the fixed carbon trajectory scenario in Figure 7, shows different dynamics for on the one hand low- and medium-income countries and on the other hand high-income countries. In the short term i.e. 2020 and long-term i.e. 2050, there is not much reduction in spending on infrastructure in high-income countries with the introduction of a fixed carbon trajectory while spending falls in both the low- and medium-income countries. In the long-term spending on infrastructure doubles in low-income countries in all three scenarios. In medium-income countries there is an increase in spending but not a doubling. Figure 7also shows that spending on road maintenance in high-income countries is greater than spending on new roads in all three scenarios, while in low-income countries spending on public transport infrastructure is as much as spending on road infrastructure. The amount of spending on maintenance reflects the amount of road infrastructure already in place. Despite Figure 7 showing that the investment needed in infrastructure increases between 2020 and 2050 Figure 8however suggests that the percentage of GDP needed for infrastructure falls between 2020 and 2050 in each scenario, obviously due to GDP increasing faster than spending on infrastructure. At the same time there is a marginal short term increase in the percentage of GDP spent on infrastructure in the in the fixed carbon trajectory scenario meaning that there is a dip in GDP. Note that long-term reduction in spending on air travel shown for middle-income countries shown in Figure 7 and Figure 8 in the two fixed carbon trajectory scenarios is offset by an increased proportion of spending on automobile and public transport infrastructure. It can also be observed in Figure 8 that the percentage of GDP spent on infrastructure is usually lower in low- and medium-income countries than in high-income countries. The range is between 1% and 2% respectively. This is because of GDP growing faster in the former countries.

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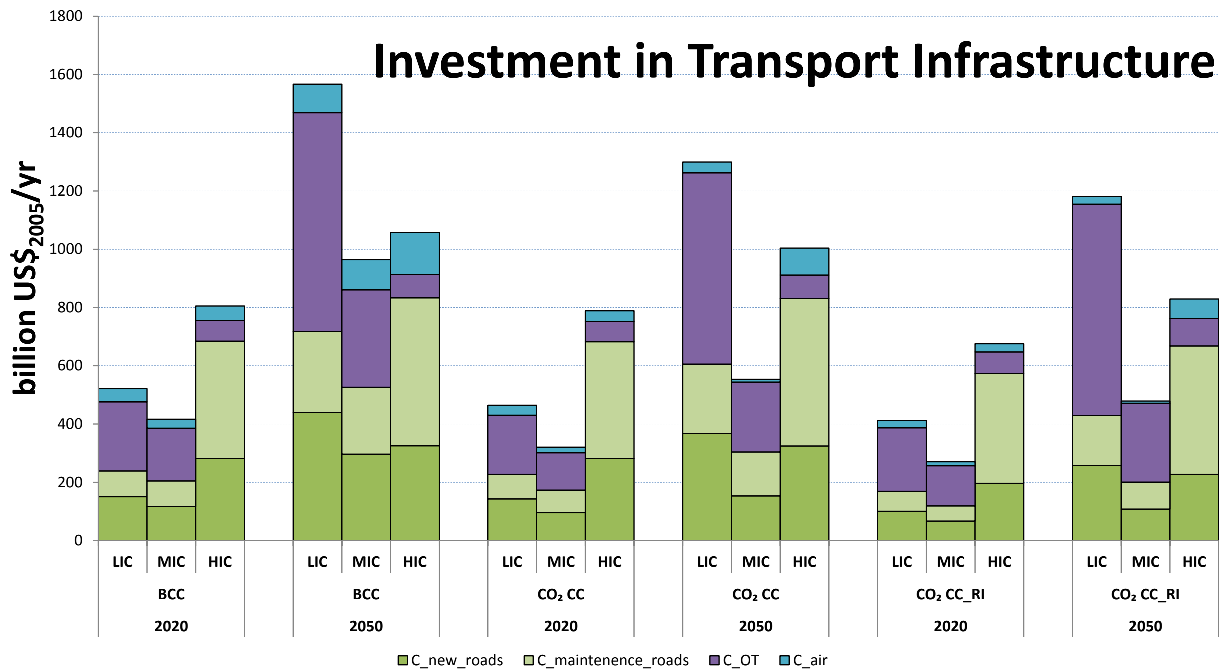

Figure 7 :Total investment cost (C) calculated to meet infrastructure deploymentand maintenance in 2020 and 2050 in three scenarios for Low-, Medium- and High-income countries.The three scenarios are labelled BCC (Scenario 2), CO_2 CC (Scenario 4), CO_2 CC_RI (Scenario 6).

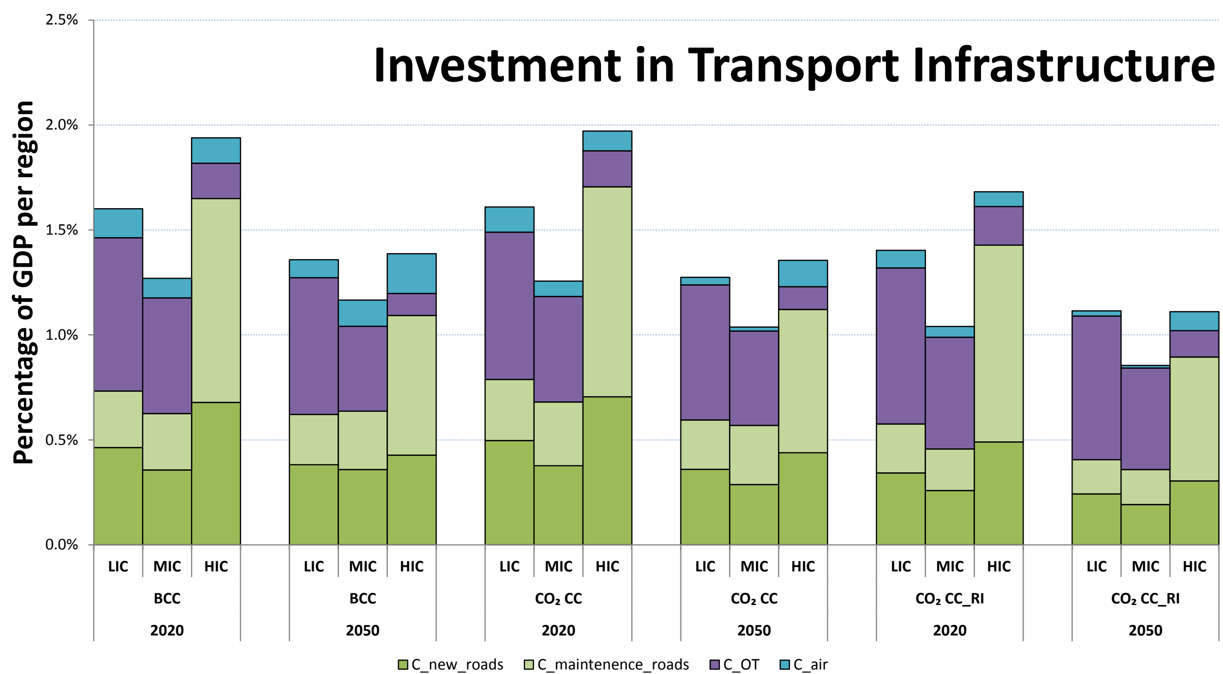

Figure 8 : Total investment cost (C) calculated to meet infrastructure deployment and maintenance as a percentage of GDP to meet infrastructure deployment in 2020 and 2050 in three scenarios for Low-, Medium- and High-income countries.The three scenarios are labelled BCC (Scenario 2), CO_2CC (Scenario 4), CO_2CC_RI (Scenario 6).

Table 4 : IMACLIM-R regions divided by income class.

High-Income	Medium-Income	Low-Income
USA	CIS	Africa
CANADA	China	India
EU	Brazil	Rest of Latin America
JANZ	Middle East	Rest of Asia

4. Discussion

By taking into consideration parameters such as the density of the existing road network and its level of utilization, the approach adopted in this work develops more realistic scenarios than the linear expansions of physical network infrastructure that have heretofore been modelled in IAMs. Examining the impact of infrastructure deployment on GDP brings additional added value to the work. The results from the modelling suggest that including costs for and constraints on the deployment of transport infrastructure has an impact of baseline values of key indicators. It also suggests that restricting infrastructure expansion results in mode shift away from automobile transport and a lowered cost for mitigation.

One of the key modelling approaches chosen in this work, the exogenous reduction of infrastructure deployment for road and air travel by 30% may however be difficult to implement as a policy measure. This is because it is a reduction on a projection and it is very difficult ex-ante to know how much infrastructure will be deployed. While in theory one could propose that in general that less automobile or air travel infrastructure be deployed at the same time however it has been observed that infrastructure is not deployed at a rate sufficient to avoid congestion. According to the Global Energy Assessment, institutions and policies that either accommodate the car or favor public transport have not been adequate, which resulting in greater congestion and poor accessibility and mobility. With well-known exceptions like Curitiba, Brazil and Hong Kong, China neither urban nor state-based institutions in developing countries have been strong and/or funded enough to accommodate rapid rates of population and motorization growth, exacerbated by the presence of sharp income inequalities(Kahn Ribeiro et al., 2012). Thus infrastructure deployment is already being *de facto* restricted.

Despite the development of the model with regard to how infrastructure for automobiles is modelled the approach for public transport and air travel has not been modified. The difference for these two modes of transport with Waisman et al., (2013) is that the cost of their deployment has been introduced into the model and the development of air transport has also been restricted in an alternative scenario (Scenarios 5 and 6 in Table 3). In an aggregated global sense there are probably few physical barriers to airport, bus or rail public transport expansion meaning that the approach used may be reasonable at least for non-OECD countries. On the other hand the costs and time needed for an expansion of airport and rail networks could be examined in more detail. The values chosen for the key parameters shown in Table 2 and the infrastructure costs listed in Table 1 can of course also be questioned. Further work could carry out a sensitivity analysis on key modelling parameters such as the 2% cap on road infrastructure spending, the density of the road network, the capacity of the construction industry to deploy infrastructure and also make the costs for infrastructure deployment evolve over time.

No feedback exists in the model between increased deployment of infrastructure and productivity. As it stands the model treats investment in concrete as being a less productive activity than investment in other sectors. Although not presented graphically above this results in the model showing lowered GDP resulting from infrastructure deployment*ceteris paribus* This can be justified in response to the discussion presented by Prud'homme, (2005) and Straub, (2008)on whether deployment of infrastructure results in increased GDP. The conclusions given were that there can be a positive relationship with GDP on some occasions but this is not guaranteed because there are other non-economic reasons for infrastructure deployment and also a lack of empirical evidence to support a linear relationship with GDP. On the other hand it could be suggested that there should be some coupling to reflect the role of big projects such as the US Interstate highway. This is also something that could be considered under further work.

Further work, could be to add charging stations for electric vehicles, andexplorethe existence of non-linear network effects related to the deployment of transport infrastructureas described by Laird et al., (2005). In addition the IMACLIM-R model could be developed to incorporate process emissions from the production of the cement used in infrastructure deployment. Such a development could compare results to the findings of Müller et al., (2013)cited in the *Introduction* about the deployment of more infrastructure. Müller's paper highlights the potential of the construction of new infrastructure to vastly exacerbate the climate problem.The IMACLIM-R modelling framework could also be used to evaluate reduced infrastructure deployment needed from measures such as increasing vehicle occupancy. In the current version of the model vehicle occupancy is a region specific constant for the entire scenario period ranging from 1.53 for USA to 1.89 for China, India and the Rest of Asia.Other automobile related policy measures such as restrictions on parking spaces could also be modelled. A limitation of the work as presented is that growth in infrastructure for reasons other than alleviating congestion, e.g. the desire to pave roads, or upgrade them to motorway, or to connect cities to ports, are not considered. This is also something that could be explored to improve the modelling.

5. Conclusion

A modelling exercise has been carried using the IMACLIM-R Global E3 integrated assessment model to explore the role of transport infrastructure in the context of (i) calibrating an accurate model baseline scenario and (ii) the cost of mitigating climate change. The exercise has involved model development to include the costs of infrastructure deployment and to better represent the deployment of automobile infrastructure. It has been found that recalibrating the baseline to include costs and constraints on the deployment of infrastructure results in a baseline which is closer to measured observations for the period 2001 to 2013 thus improving the calibration of the baseline. It has also been found that in a scenario where the deployment of infrastructure is restricted (e.g. as a policy measure) in addition to a fixed carbon trajectory constraint being applied, the GDP loss is less than with the fixed carbon trajectory constraint only. This suggests that restricting infrastructure deployment in a fixed carbon trajectory scenario lowers the cost of mitigation i.e. the cost premium for a low-carbon energy system can be partially offset by restring road and air travel infrastructure deployment. The application of the methodology in the IMACLIM-R Global E3 IAM model has thus shown how baseline scenarios can be improved and also how macroeconomic and mitigation effects can be better explored by having an infrastructure lever included in IAM models.

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