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Freight Futures: The Potential Impact of Road Freight on Climate Policy

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Summary

This paper describes changes to the modelling of the transport sector in the WITCH (World Induced Technical Change Hybrid) model to incorporate road freight and account for the intensity of freight with respect to GDP. Modelling freight demand based on the intensity of freight with respect to GDP allows for a focus on the importance of road freight with respect to the cost-effective achievement of climate policy targets. These climate policy targets are explored using different GDP pathways between 2005 and 2100, which are sourced from the Shared Socioeconomic Pathways (SSPs) database. Our modelling shows that the decarbonisation of the freight sector tends to occur in the second part of the century and the sector decarbonises by a lower extent than the rest of the economy. Decarbonising road freight on a global scale remains a challenge even when notable progress in biofuels and electric vehicles has been accounted for.

Keywords: Road Freight, Transport, Climate Mitigation, Integrated Assessment Models

JEL Classification: Q54, Q58, R41

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Abstract

This paper describes changes to the modelling of the transport sector in the WITCH (World Induced Technical Change Hybrid) model to incorporate road freight and account for the intensity of freight with respect to GDP. Modelling freight demand based on the intensity of freight with respect to GDP allows for a focus on the importance of road freight with respect to the cost-effective achievement of climate policy targets. These climate policy targets are explored using different GDP pathways between 2005 and 2100, which are sourced from the Shared Socioeconomic Pathways (SSPs) database. Our modelling shows that the decarbonisation of the freight sector tends to occur in the second part of the century and the sector decarbonises by a lower extent than the rest of the economy. Decarbonising road freight on a global scale remains a challenge even when notable progress in biofuels and electric vehicles has been accounted for.

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1. Introduction

The demand for freight transport has been evolving based on the transformation of economies across the globe. Within the most recent IPCC WG3 report (Section 8.9.1) it was noted that while integrated assessment models project that freight transport emissions will increase at a slower pace than passenger transport, notable emission increases will still occur. Based on the IAMC (Integrated Assessment Models Community) scenario database, the IPCC report notes that freight transport emissions will "rise by as much as threefold by 2050 in comparison to 2010 levels [and that] freight demand has historically been closely related to GDP" (Sims et al., 2014). Reviewing the future of freight is important as it is a sector that will be difficult to decarbonise before the middle of the century and in a range of IAMs the sector remains dependent upon liquid fuels that can only be partially decarbonised through the use of biofuels (Capros et al., 2012 and Pietzcker et al., 2013). Indeed, Chapman (2007) noted that while technological break-through in fuels, fuel efficiency improvements and routing/scheduling will impact emissions and be important, the major challenge for freight is that demand continues to grow. He also noted that improved logistics and efficient vehicle loading are the most viable solutions until technological advances, dematerialisation and modal shift can have a significant impact on emissions. With respect to the challenge of decarbonising freight, Eom et al. (2012) noted that growth in freight transport emissions tended to outpace passenger transport emissions in most of the eleven IEA countries they focused upon in the period between 2007 and 2010. In addition, they found that there was little evidence of a shift away from road freight and that growth in trucking was higher than that seen in rail and water freight for most of the IEA countries reviewed.

In order to investigate the importance of freight with respect to differing demand and climate policies, this paper develops projections of freight demand which are evaluated based on the intensity of road freight with respect to GDP for 62 countries between 1990 and 2010. The freight intensity of GDP is then applied to three sets of GDP pathways between 2005 and 2100, which are sourced from the Shared Socioeconomic Pathways (SSPs) database, and three carbon policy scenarios. A matrix of nine scenarios is defined in order to explore the different road freight futures under different economic and climate mitigation settings. Implementing these scenarios in the WITCH (World Induced Technical Change Hybrid) model allows for an analysis of the challenge that decarbonising road freight with technological advances presents when modal shift and reduced freight demand are not viable options. The WITCH model has been chosen as the basis of the analysis as it is an integrated assessment model with a detailed representation of road transport that includes demand intensity based on GDP, vehicle composition of the fleet and technological advances in biofuel and battery technologies. Chapman (2007) identified five alternate fuels and vehicles that are likely to be related to decarbonisation of road transport. Amongst these five vehicle options, the WITCH model contains endogenous and flexible modelling of advances in biofuels, hybrid electric vehicles and battery powered vehicles, but does not model gaseous fuels and fuel cell vehicles as decarbonisation options.

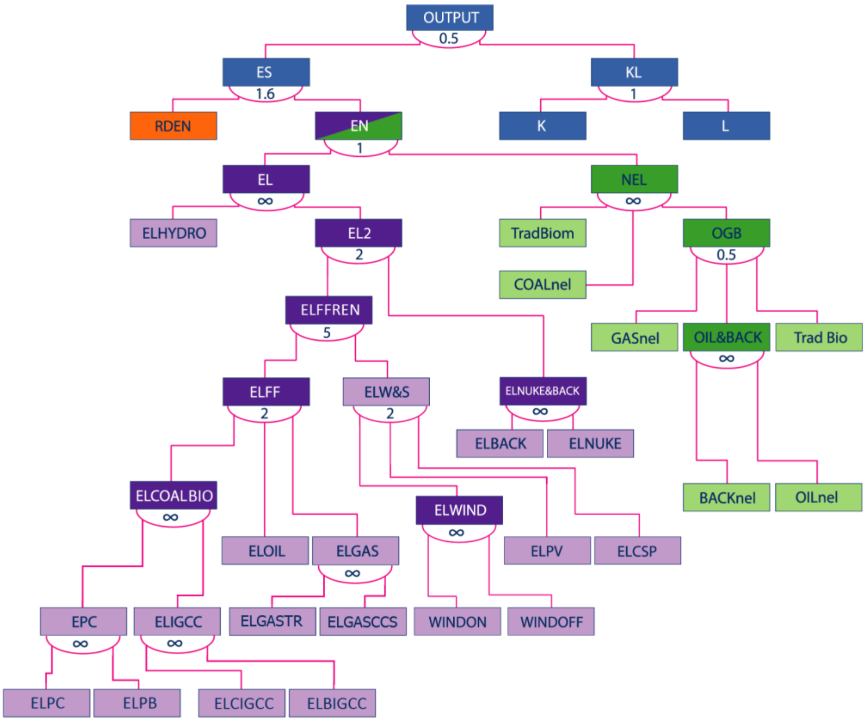
Within Bosetti and Longden (2013), this model was adapted to analyse the passenger road transport sector, focusing in particular on Light Duty Vehicles (LDVs) and specifically assessing the importance of Electric Drive Vehicles (EDVs) in achieving cost-effective climate policy targets. This paper will utilise a revised version of the same model that has been expanded to include a road freight module and perform a similar analysis as the previous paper with a focus on the importance of freight. In doing so, the paper will aim at highlighting how important the decarbonisation of the freight sector may be in the future given different GDP pathways and mitigation targets. With total demand exogenously fixed, the crucial factor will then be the amount of decarbonisation that can occur at least cost within the road freight sector, as opposed to other sectors.

Section 2 provides a description of the modelling of road freight within WITCH, as well as clarifying the range of decarbonisation options available within the model and describing the main calibration data utilised in the model. Section 3 focuses on freight demand and the freight intensity seen in historical data. Section 4 provides detail on the GDP and climate policy scenarios that are utilised in the subsequent section. Section 5 shows and discusses the results of the analysis in terms of the number of freight vehicles necessary to meet the differing levels of freight demand, the fleet composition, the fuel mix and the contribution of the sector in decarbonising the economy under the explored scenarios. Section 6 concludes this paper with an overview of the findings discussed in the paper.

2. Modelling Road Freight in WITCH

WITCH is an integrated assessment model that aims at developing optimal scenarios to study the energy, economic and environmental dimensions of climate change in the 21st century, starting from 2005. It is defined as a hybrid model because it combines characteristics of top-down and bottom-up modelling: the top-down part consists of an inter-temporal optimal growth Ramsey-type model that is combined with a detailed and disaggregated description of the energy sector, which is the bottom-up part of the model. The model is structured using a Constant Elasticity of Substitution (CES) framework, schematised in Figure 1.

Figure 1. The CES structure in WITCH.



The aggregated nodes of capital (K) and labour (L) are combined with each other and this is then combined with the overall energy services node (ES) to produce the economic output of the model. Energy is divided into the capital of energy R&D (RDEN) and the actual energy generation (EN). Energy generation is computed using a nested production function resulting from the aggregation of different technologies with different elasticities of substitution. The first distinction is between the electric (EL) and non-electric sector (NEL), with a progressive disaggregation down to the single technologies. A thorough description of the CES structure is reported in Carrara and Marangoni (2016).

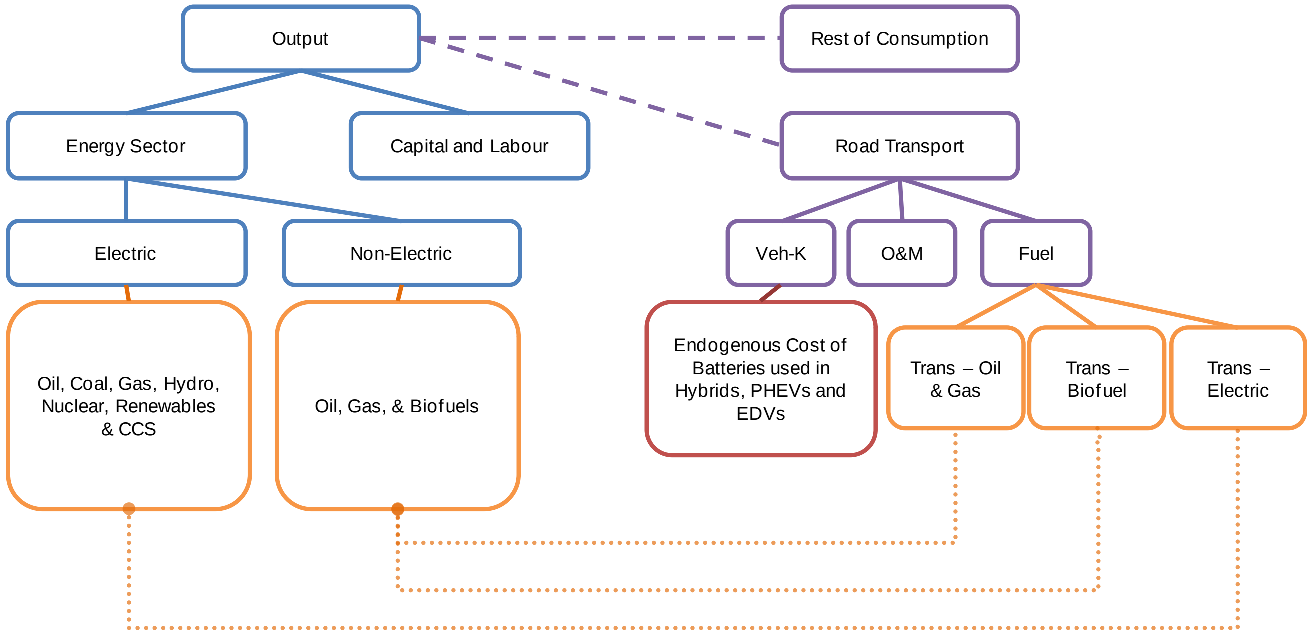
The transport sector is defined in two distinct sections of the model. The whole transport sector with the exception of road passenger (LDVs only) and road freight is captured in the aggregated non-electric tree. LDVs and road freight, instead, are explicitly modelled in a way which will be described shortly and do not directly appear in this CES structure.

The model is defined on a global scale: world countries are grouped into thirteen regions, defined on the basis of geographical or economic coherence. The regions behave independently but do interact with each other through a non-cooperative Nash game. The thirteen economic regions are USA (United States), WEURO (Western EU and EFTA countries), EEURO (Eastern EU countries), KOSAU (South Korea, South Africa and Australia), CAJAZ (Canada, Japan and New Zealand), TE (Transition Economies, namely Russia and Former Soviet Union states and non-EU Eastern European countries), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa except South Africa), SASIA (South Asian countries except India), EASIA (South-East Asian countries), CHINA (People's Democratic Republic of China and Taiwan), LACA (Latin America and Central America) and INDIA (India). Technological change in energy efficiency and specific clean technologies is endogenously modelled, reacting to price and policy signals. All economic quantities are expressed in 2005 US dollars. A more detailed description of the model can be found in Emmerling et al. (2016) and on the model websites: www.witchmodel.org and http://doc.witchmodel.org/.

As previously discussed, Bosetti and Longden (2013) describes how the LDV sector has been explicitly modelled in WITCH. The road freight module has now been introduced using a similar modelling scheme. This paper discusses the modelling approach used and highlights the differences made to accommodate a road freight model.

Figure 2 shows the transport sector model within the WITCH model structure. The left side of the figure contains a more aggregated representation of the CES structure that was shown in Figure 1 and this part of the model is highlighted in blue. The transport sector is connected to the rest of the model through two links. One of these links the transport model to the aggregated macroeconomic part of WITCH model (top) and the other links the transport model to the energy sector within the WITCH model (bottom).

Figure 2. Road transport model within WITCH.



To accommodate a transport sector, the model separates consumption in transport from the rest of consumption. This separation allows for a direct modelling of the costs involved in switching between vehicles and fuels for a given demand of mobility. As a result, investments in vehicle capital and supplementary costs decrease the level of consumption. Equations from 1 to 3 detail this concept in formula. The model will thus find a solution which minimises consumption loss given the demand for mobility, freight and other relevant constraints.

In each region, indexed by n, a forward-looking central planner maximises the total discounted welfare W, refer to Equation 1 for this specification. Time is denoted as t; L is labour (i.e. population); C is consumption, while β and η are the utility discount factor and the inverse of the intertemporal elasticity of substitution, respectively. β is calculated as $(1+\rho)^5$, where ρ is the pure rate of time preference and is set equal to 1%, while 5 indicates the 5-year time spans adopted in WITCH; η is fixed to 1.5.

$$W(n) = \sum_t L(t,n) \frac{\left(\frac{C(t,n)}{L(t,n)}\right)^{1-\eta} - 1}{1-\eta} \cdot \beta^t \tag{1}$$

Equations 2 and 3 represent the distinction between the aggregate level of consumption (CG) and the level of consumption net of transport (C). CG is defined by the budget constraint represented in Equation 2 where Y is output (i.e. GDP), I_{fg} are investments in final good, I are investments in the different energy technologies (indicated with j), $I_{R\&D}$ are investments in R&D that lower the cost of technology j, and O&M represents the expenditures in the operation and maintenance of technologies in the energy sector. All quantities are evaluated on a yearly basis.

$$CG(t,n) = Y(t,n) - I_{fg}(t,n) - \sum_j I_{R\&D}(j,t,n) - \sum_j I(j,t,n) - \sum_j O\&M(j,t,n) \tag{2}$$

The aggregate level of consumption net of transport expenses is given by gross consumption subtracted by the cost of road transport, including, for each type of vehicle (veh): investments in road vehicles (I), investments in research related to battery technologies ($I_{R\&D,batt}$), operation and maintenance of the vehicles (O&M) and the fuel expenditure (FE) for each fuel f.

$$\begin{aligned} C(t,n) &= \\ &= CG(t,n) - \sum_{veh} I(veh,t,n) - I_{R\&D,batt}(t,n) - \sum_{veh} O\&M(veh,t,n) - \sum_{veh}\sum_f FE(veh,f,t,n) \end{aligned} \tag{3}$$

A Leontief production function combines the investment, operation & maintenance, and fuel costs associated with each vehicle type. The transport sector’s demand for fuels (oil, traditional biofuels, advanced biofuels and electricity) competes with demand from other sectors and this explains the second link in Figure 2 that is highlighted in orange.

The total number of vehicles is set equal to a projection depending on the reference calibration of GDP and population growth. Hence, this projection is not part of the optimisation process. For freight, the number of vehicles grows at a rate equal to the GDP per capita growth based on historical data. This historical data is from a selected set of OECD countries (United States, Western Europe, Japan, and Australia) and is sourced from Fulton and Eads (2004) who focused on three 5-year periods from 1984 to 1999. The growth in vehicles tended to be between 96% and 114% of GDP per capita growth (Fulton and Eads, 2004). For LDVs, the calculation follows a complex scheme described in the same reference (Fulton and Eads, 2004), which in turn is based on Dargay and Gately (1999). Refer to Bosetti and Longden (2013) for details of the LDV calculation. To set the initial stock of vehicles we have used a range of references, including Fulton and Eads (2004), Dargay et al. (2007), Fulton et al. (2009) and various reports focused on individual countries.

Note that while the number of vehicles is based on the GDP levels that coincide with the scenario used to calibrate the model, the fleet composition is determined by the optimisation process. Starting from a fixed value for the first time period (2005), Equation 4 sets the subsequent capital stock of road vehicles (K) in each period equal to the level of capital remaining after depreciation (δ is the yearly depreciation rate)[1] and accounting for the additional capital that is implied by investments undertaken at the investment cost of vehicles (SC).

$$K(veh,t+1,n) = (1-\delta)^5 \cdot K(veh,t,n) + 5 \cdot I(veh,t,n)/SC(veh,t,n) \qquad (4)$$

As there is a linear competition between the types of vehicles modelled that is based on cost considerations that are not moderated by lower-than-infinite elasticities, irregular patterns may result without additional model constraints. For example, we aim to prevent a sudden switch from one technology to another. Accordingly, we introduce a set of restrictions or constraints which weaken this effect. One example is given by the growth curves applied within the model as an endogenous constraint upon the introduction of interim technology options. The following logistic functional form has been implemented in WITCH to mitigate rapid shifts to alternative vehicle types:

$$K(veh,t+1,n) - K(veh,t,n) < 1.124 \cdot \left(1 - \frac{K(veh,t,n)}{\sum_{veh} K(veh,t,n)}\right) \cdot K(veh,t,n) \qquad (5)$$

where the numerical factor (1.124) has been derived by fitting the hybrid vehicle projections reported in IEA (2010).

WITCH distinguishes between four types of vehicles and this applies to both the passenger and the freight sectors: Traditional Combustion Engine (TCE) vehicles, Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEVs) and Electric Drive Vehicles (EDV)[2,3]. The final cost for the electric vehicles is given by the sum of the traditional vehicle parts and the battery equipment, which is in turn given by the product between the battery size and the battery unitary investment cost[4]. The investment cost for traditional combustion vehicles is held constant at 2005 levels, while the battery cost decreases according to a learning-by-researching

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[1] The rate of depreciation is set to reflect a replacement of vehicles occurring every 22 years. Within this version of the model, no distinction has been made for the existence of used vehicles other than an extended first use lifetime of 22 years.

[2] In other references in the literature EDVs are sometimes referred at as Battery Electric Vehicles (BEVs).

[3] In the absence of different indications, the acronyms will refer to trucks only henceforth.

[4] In the case of EDVs, the cost of the traditional vehicle part is reduced by 25% due to the absence of the internal combustion engine.

scheme, i.e. it is determined by dedicated investments in R&D. An exogenously fixed decreasing path calibrated using Nykvist and Nilsson (2015) – and shown in Figure 3 – is set as an upper bound for all regions and additional investments in the different regions generate further local cost reductions (refer to Bosetti and Longden (2013) and Longden (2014) for details on the battery learning modelling). Table 1 summarises the battery size and the initial cost for the four types of trucks modelled in WITCH.

Figure 3. Upper bound for the battery cost.

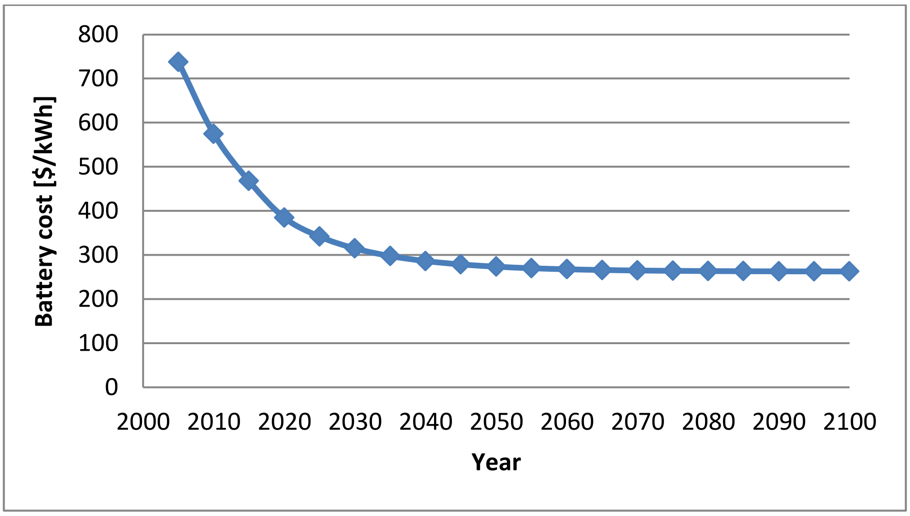

Table 1. Battery size and initial cost for freight vehicles.

Vehicle type	Battery size [kWh]	Initial cost (2005) [$]
TCE	-	154000
HEV	8.75	165000
PHEV	78.75	253000
EDV	262.5	445000

Energy consumption associated to the different vehicle types linearly depends on the number of vehicles, the kilometre demand (km_d) and the specific fuel consumption (fc):

$$Q(veh,t,n) = km\_d(n) \cdot fc(veh,t,n) \cdot K(veh,t,n) \tag{6}$$

Fuel consumption is specified as the energy consumed by each vehicle for covering one kilometre. For traditional trucks this value is about 12-16 MJ/km depending on the region and it is around 2.5-3 MJ/km, i.e. 0.7-0.8 kWh/km, for EDVs. HEVs and PHEVs have intermediate values between these extremes. The specific fuel consumption exponentially decreases over time in order to simulate advancements in vehicle efficiency.

This is an approximately halving of fuel consumption by the end of the century and this is in line with Fulton and Eads (2004). Kilometre demand represents the number of kilometres covered by each vehicle over the year. The functional dependency in Equation 6 shows that this value varies across regions, but it is kept constant over time. A detailed analysis of the freight kilometre demand in the different regions is reported in Section 3. Here it is useful to note that service demand (s_d henceforth) indicates the number of tonne kilometres travelled per year and it is given by the multiplication between the kilometre demand and the so-called load factor (lf), which indicates the number of tonnes of freight averagely carried by each truck[5].

Finally, in addition to Equation 5, other constraints are imposed in the model. These include:

- a limit on the amount of biofuel that can be used in each vehicle: a maximum of 50/50 biofuel/oil mixture is allowed up to 2020, then the limit progressively relaxes reaching the level of 100% allowed biofuel share in 2100 (i.e. the whole vehicle fleet – except obviously for EDVs – is supposed to be equipped with E100 engines); and
- a restriction which constrains investments in each vehicle family to at least 30% of the previous period, which is intended to prevent investments disappearing in an interim technology at too fast a pace.

3. Projections of Freight Demand

In order to project freight demand into the future, current demand should first be reviewed so as to adequately set the parameters of interest within the model. Coherently with the other modelling assumptions, Fulton and Eads (2004) has been taken as a source for this calibration data. The derived numbers have then been compared to a collection of historical data concerning the intensity of tonne kilometres with respect to GDP (road freight intensity henceforth) across countries for the period between 1990 and 2010. This data has been sourced from World Bank (2013).

In Fulton and Eads (2004) road freight vehicles are divided into heavy-duty and medium-duty trucks. This is a level of detail which has been deemed to be unnecessary for an IAM like WITCH. In accordance the data has been aggregated into one single category with a weighted average for the number of vehicles in each class. Table 2 reports kilometre demand and load factor for the year 2000. Note that these values will be kept constant in WITCH. The regional aggregation in Fulton and Eads (2004) substantially overlaps with the regions in WITCH and thus it is possible to associate the relevant data with a limited loss of accuracy[6].

As the comparison data from the World Bank is provided as the intensity of tonne kilometres with respect to GDP, it is necessary to calculate the service demand per vehicle, then the total service demand (by multiplying the former value by the total number of vehicles), and finally the abovementioned intensity (by dividing the obtained quantity by the regional GDP). Table 3 reports these calculations.

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[5] The general expression "freight demand" does not refer explicitly to any specific quantity, and might refer to both kilometre demand and service demand when a general statement on the freight sector is made.

[6] The mapping of these regions is as follows: OECD North America → USA; OECD Europe → WEURO; OECD Pacific → KOSAU and CAJAZ; Former Soviet Union → TE; Eastern Europe → EEURO; China → CHINA; Other Asia → SASIA and EASIA; India → INDIA; Middle East → MENA; Latin America → LACA; Africa → SSA.

Table 2. Kilometre demand – expressed in km/(veh·yr) – and load factor – expressed in ton/veh.

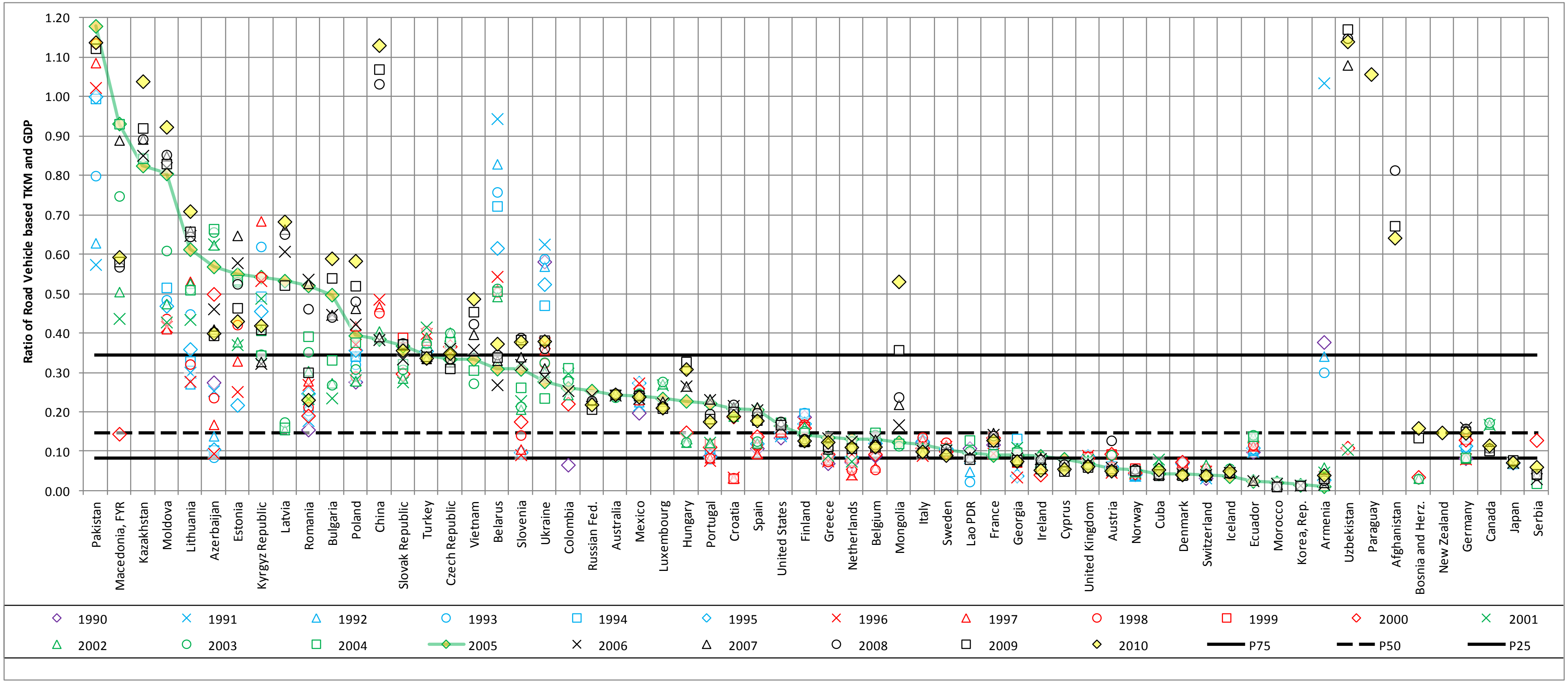
	Medium-duty			Heavy-duty			Average	
	Number of trucks	km_d	lf	Number of trucks	km_d	lf	km_d	lf
OECD North America	4011224	32000	2.2	4758797	60000	10	47193	6.43
OECD Europe	4700257	25000	1.7	4207926	60000	8	41533	4.68
OECD Pacific	3578226	25000	1.5	652281	60000	8	30396	2.50
Former Soviet Union	1214207	25000	1.7	485321	50000	8	32139	3.50
Eastern Europe	2391756	20000	1.7	243959	50000	6	35149	3.87
China	2132804	20000	1.7	725153	50000	6	27612	2.79
Other Asia	3513285	20000	1.7	2256310	50000	6	31732	3.38
India	1396742	20000	1.7	897019	50000	6	31732	3.38
Middle East	4661400	22000	1.7	1355950	50000	6	28310	2.67
Latin America	4738565	22000	1.7	2362964	50000	6	31317	3.13
Africa	1123720	20000	1.7	509420	50000	6	29358	3.04

Table 3. Road freight intensity (WITCH).

	km_d [km/ (veh ·yr)]	**lf [ton/veh]**	**s_d [tkm/ (veh ·yr)]**	**Vehicle number (2005) [veh]**	**s_d tot (2005) [billion tkm/yr]**	**GDP (2005) [billion $/yr]**	**Road freight intensity (2005) [tkm/$]**
USA	47193	6.43	303451	7893018	2395	12883	0.186
WEURO	41533	4.68	194374	7908183	1537	13784	0.112
EEURO	35149	3.87	136027	1241567	169	839	0.201
KOSAU	30396	2.50	75990	1584559	120	1882	0.064
CAJAZ	30396	2.50	75990	3826913	291	5898	0.049
TE	32139	3.50	112487	1941096	218	1970	0.111
MENA	28310	2.67	75588	6517350	493	2078	0.237
SSA	29358	3.04	89248	1133140	101	505	0.200
SASIA	31732	3.38	107254	1096223	118	224	0.525
CHINA	27612	2.79	77037	2857957	220	3002	0.073
EASIA	31732	3.38	107254	3577149	384	1027	0.374
LACA	31317	3.13	98022	7101529	696	3016	0.231
INDIA	31732	3.38	107254	2293761	246	848	0.290

Figure 4 reviews the road freight intensity values sourced from the World Bank for an unbalanced dataset of 62 countries between 1990 and 2010 and this results in a total of 790 observations. The observations for 2005 and 2010 have been highlighted in yellow as these time periods align with the first two periods of the WITCH model (it should be noted that 2005 values are not available for all the considered countries).

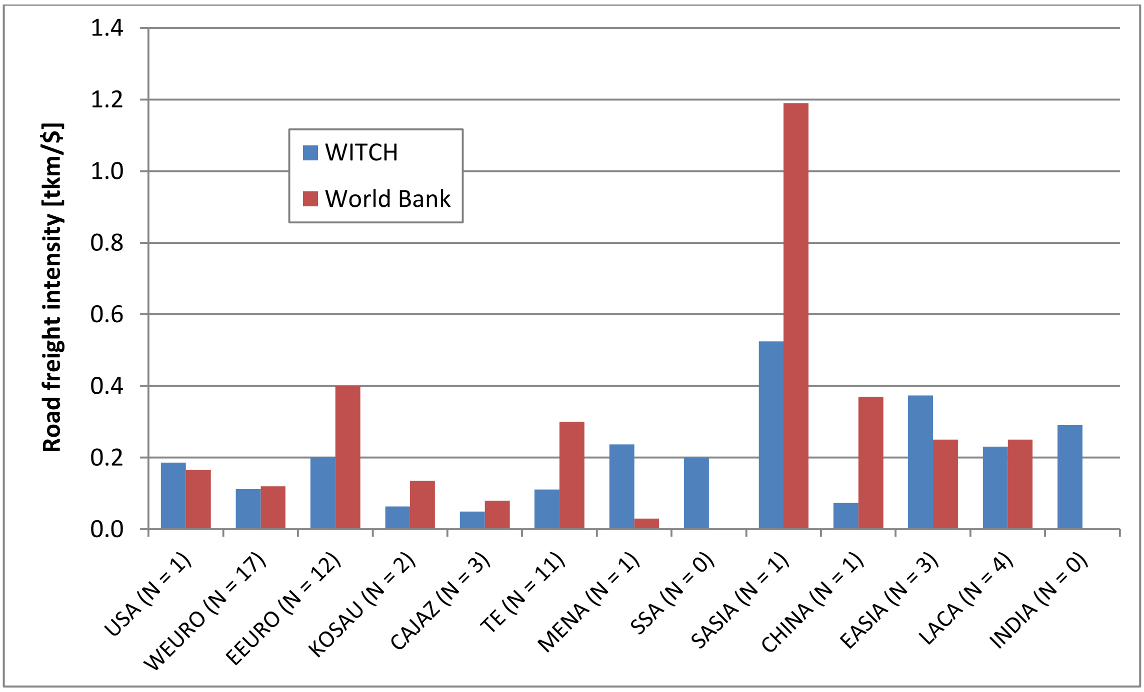
Figure 4. Road freight intensity between 1990 and 2010 (tkm/2005USD).



With a median of 0.148, a 25th percentile of 0.083 and a 75th percentile of 0.334 across the whole data sample, there is an interesting range of countries with road freight intensity within this bound. A selected range of countries for 2005 includes the Czech Republic (0.334), Vietnam (0.334), the Russian Federation (0.254), Australia (0.244), Mexico (0.241), Luxembourg (0.234), the United States (0.165), Finland (0.142), Greece (0.135), Mongolia (0.123), Italy (0.119), France (0.090) and Ireland (0.088). Of these countries, the increase between 2005 and 2010 was highest in Mongolia (331%) followed by Vietnam (46%) and France (42%), with decreases highest in Ireland (40%) followed by Italy (16%), the Russian Federation (14%), Finland (10%), Luxembourg (10%) and Greece (9%). Above the median and past the 75th percentile the variance across periods increases. Countries such as Pakistan, Moldova and Lithuania show notable increases over time, while China, Belarus and Ukraine show decreases in road freight intensity. The countries under the 25th percentile tend to have small variance over time. Countries with consistently low road freight intensity within this group include Norway, Cuba, Denmark, Switzerland, Iceland, Morocco, R. of Korea, Armenia and Japan.

Figure 5 compares the values for the road freight intensity obtained from Fulton and Eads (2004) – and implemented in WITCH – and those from the World Bank. Beside each region name, the parameter N indicates how many countries have been mapped into each region. Note that no 2005 values are available for the three CAJAZ countries (Canada, Japan, New Zealand), while all of them report 2010 data. As a result, values from the latter year have been shown in the table.

Figure 5. Comparison of road freight intensities in 2005 (WITCH and World Bank).



The two datasets show a good level of consistency even if some non-negligible differences can be seen. In general, the WITCH data tends to be an underestimate in comparison to the World Bank data. In some cases, and especially in non-OECD regions, a limited number of countries prevents a proper comparison. This is particularly true for MENA, EASIA, LACA, and partly SASIA, where Pakistan, being by far the country characterised by the highest intensity, determines the average value of the region. World Bank data for SSA and INDIA are not available. USA and WEURO values are practically identical, while TE and especially CHINA have great divergence and this suggests that a more in-depth review should be carried out in order to find more consolidated data. In general, it is noticeable that most of the non-OECD regions have higher freight intensity in comparison to the OECD and this reflects the profile of these economies with relatively high levels of industry and a relatively low service sector.

4. Scenario Setup

The analysis performed in this paper is based on a matrix of nine scenarios that have been built by combining two major drivers, GDP and climate mitigation policy. GDP has been chosen as it is a major driver of the demand for freight. Mitigation policy has been chosen as the aim of the paper is to analyse the role of road freight in carbon mitigation. All scenarios have been conceived in coherence with the wider research activity conducted as part of the ADVANCE project and its second work package, WP2. Edelenbosch et al. (2016a and 2016b) are the two overview papers of the multi-model exercise dedicated to the transport sector, that this paper is part of.

Concerning GDP the analysis focuses on three Shared Socioeconomic Pathways (SSPs) projections of GDP between 2005 and 2100 (O'Neil et al., 2014). In particular, the SSP1, SSP2 and SSP3 GDP pathways have been considered. SSP2 is the middle of the road scenario, where the social and economic drivers tend to follow the historical patterns. SSP1 and SSP3 are scenarios which show low and high mitigation and adaptation challenges, respectively. In the SSP framework, these broad descriptions are the combination of a number of hypotheses and modelling assumptions that cover social, economic, and political dimensions. In this exercise, however, only the corresponding GDP assumptions have been adopted, while all the other modelling options have been maintained set at the WITCH model's default case (i.e. SSP2). Intuitively, the SSP2 scenario provides an intermediate economic growth scenario, while SSP1 and SSP3 denote high and low economic growth scenario, respectively.

Concerning the mitigation policies, first of all a baseline case has been considered where no mitigation policies are implemented and this scenario is called BASE. Then two carbon mitigation policies are utilised with the application of a carbon tax on greenhouse gas (GHG) emissions starting from 2020. The stronger scenario (indicated as 450) aims at achieving the long-term target of reaching a concentration of GHG in the atmosphere equal to 450 ppm-CO2eq in 2100, which roughly corresponds to 2°C of global temperature increase with respect to the pre-industrial levels. The milder one (indicated as CTAX) features the implementation of an intermediate carbon tax, whose value has been agreed upon in the ADVANCE exercise, and that in WITCH leads to a temperature increase of 2.5°C[7].

Figure 6 shows the three global GDP pathways and the two carbon tax pathways[8] for the 21st century.

It should be noted that GDP losses, which characterise the mitigation cases, do not influence the number of freight vehicles in the transport sector as the calibration of GDP occurs before the potential GDP losses related to the policy implementation are accounted for in the relevant calculations. So while the aggregate number of freight vehicles change for each SSP specification, all the policy cases are actually characterised by the same number of vehicles.

The final nine scenarios have a name that is derived from the combination of the two sets of scenarios, i.e. SSP1_BASE, SSP2_BASE, …, SSP1_CTAX, etc.

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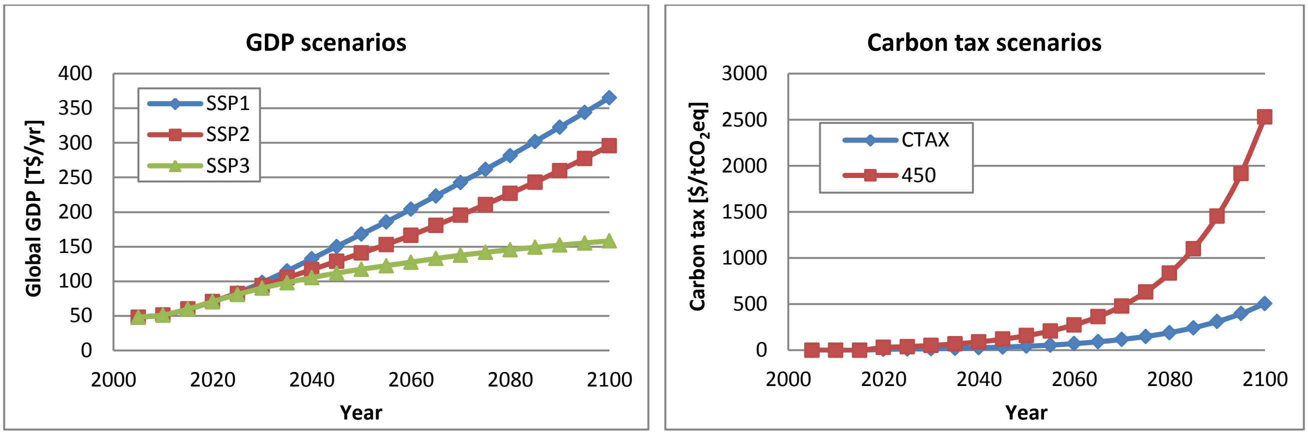
[7] Note that the scenario names have been chosen in coherence with the ADVANCE exercise.

[8] BASE can obviously be considered as a zero carbon tax scenario.

Figure 6. GDP and carbon tax assumptions.

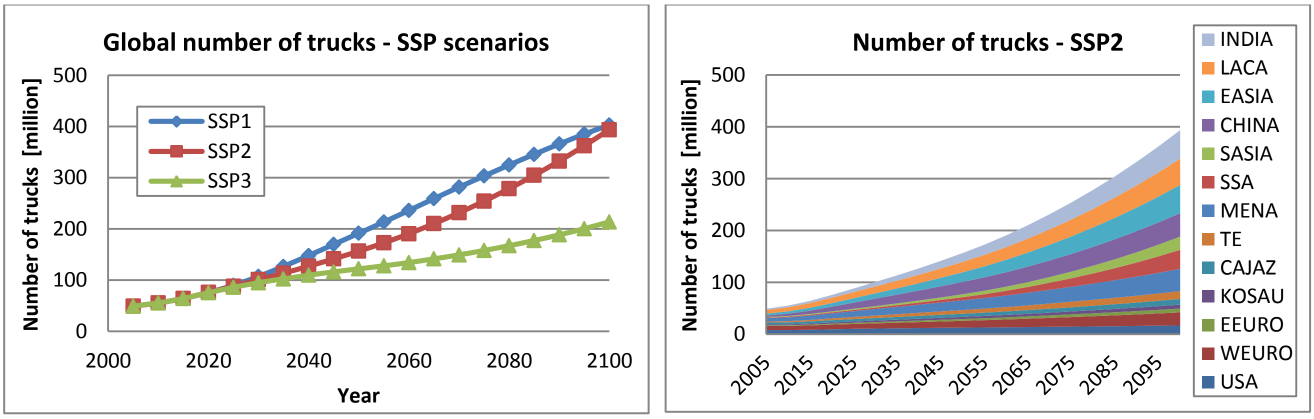


5. Results: Future of Road Freight

Having specified the scenario framework and the transport sector model used within this paper, this section contains a detailed review of the results relating to differing demands for freight as explored through the different GDP scenarios and the impacts that the mitigation policies have on the fleet composition, emissions and other relevant variables. In this paper, our focus is on the global impact of the freight sector on decarbonisation pathways.

Figure 7 provides the number of road freight vehicles that the WITCH model projects for the SSP scenarios at a global level (left) and provides regional detail for the SSP2 scenario (right). The number of vehicles tends to follow the GDP patterns. Since the kilometre demand per vehicle and the load factor are constant, the overall kilometre demand and service demand closely follow the number of vehicles. Concerning the latter, the higher GDP growth in non-OECD countries in comparison to the OECD countries leads to higher shares of road freight vehicle in those areas of the world.

Figure 7. Number of trucks: SSP scenarios (left) and regional detail in the SSP2 scenario (right).



To assess the role of road freight in global carbon mitigation we focus on the associated carbon dioxide emissions and compare them with the overall CO_2 emissions from the fossil fuel & industry sector (FF&I)[9]. The pathways of carbon dioxide emissions for the three policy cases is shown in Figure 8 for the SSP2 GDP

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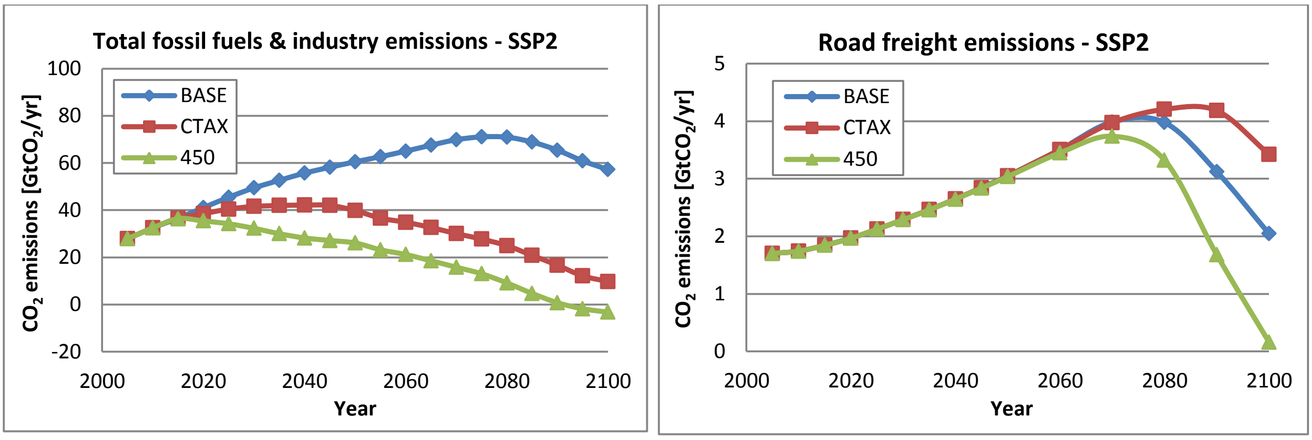
[9] Note that emissions from land use, deforestation, and the other similar sectors are not included in the comparison.

assumption. The figure compares emissions from the road freight sector and those from the whole fossils fuels & industry sector. In 2005, emissions from road freight were about 6% of the total[10]. The pattern of total FF&I emissions clearly reflects the applied mitigation policy and until 2020 (i.e. until the application of the carbon tax) emissions behave identically in the three cases. Then, in the BASE scenario they continue to grow until the latter part of the century. In comparison, the CTAX scenario has total FF&I emissions growing until the middle of the century and in the 450 scenario emissions immediately decrease and they reach negative values in the latter part of the century. These negative emissions are due to the implementation of biomass carbon capture and storage (CCS) technologies. In contrast, the progress of road freight emissions is more peculiar. No differences in emissions are shown until the second part of the century due to limited carbon mitigation options. After 2060 a strong differentiation takes place. In the 450 scenario, emissions rapidly decline towards zero in a few decades and in the other two scenarios emissions markedly decrease but not to the same extent. In the case of road freight, we have a counter-intuitive result as emissions in the CTAX case are higher than those in the BASE case. Note that the same happens in the SSP1 high growth case, but not for the SSP3 low growth case. The reason for this behaviour is due to the fleet composition and the fuel mix, which are described further on.

Figure 8. Carbon dioxide emissions from the fossil fuels & industry sector (left) and from the road freight sector (right) in the three SSP2 policy cases.



In order to compare all of the nine scenarios, Figure 9 reports the cumulative CO_2 emissions in the 21st century from the fossil fuels & industry sector (shown on the right axis) and the share of the cumulative emissions from the road freight sector (shown on the left axis). Within each SSP scenario, cumulative emissions of the three mitigation policies show predictable results in the light of what reported in Figure 8. Cumulative emissions are highest in the BASE scenario, then come those in the CTAX scenario and finally those of the 450 scenario. Absolute values vary quite markedly across SSPs as a result of the different GDP assumptions. Generally, higher economic development implies higher emissions. In the BASE case the cumulative FF&I emissions in the high growth SSP1 scenario are higher than the central SSP2 case by about 13%, while the emissions associated with the low growth SSP3 scenario are lower than SSP2 by about 22%. These differences are similar to the differences in cumulative GDP. With respect to the central SSP2 scenario, GDP is higher by 19% in the SSP1 scenario and lower by 27% in the SSP3 scenario. Comparing the cumulative emissions across

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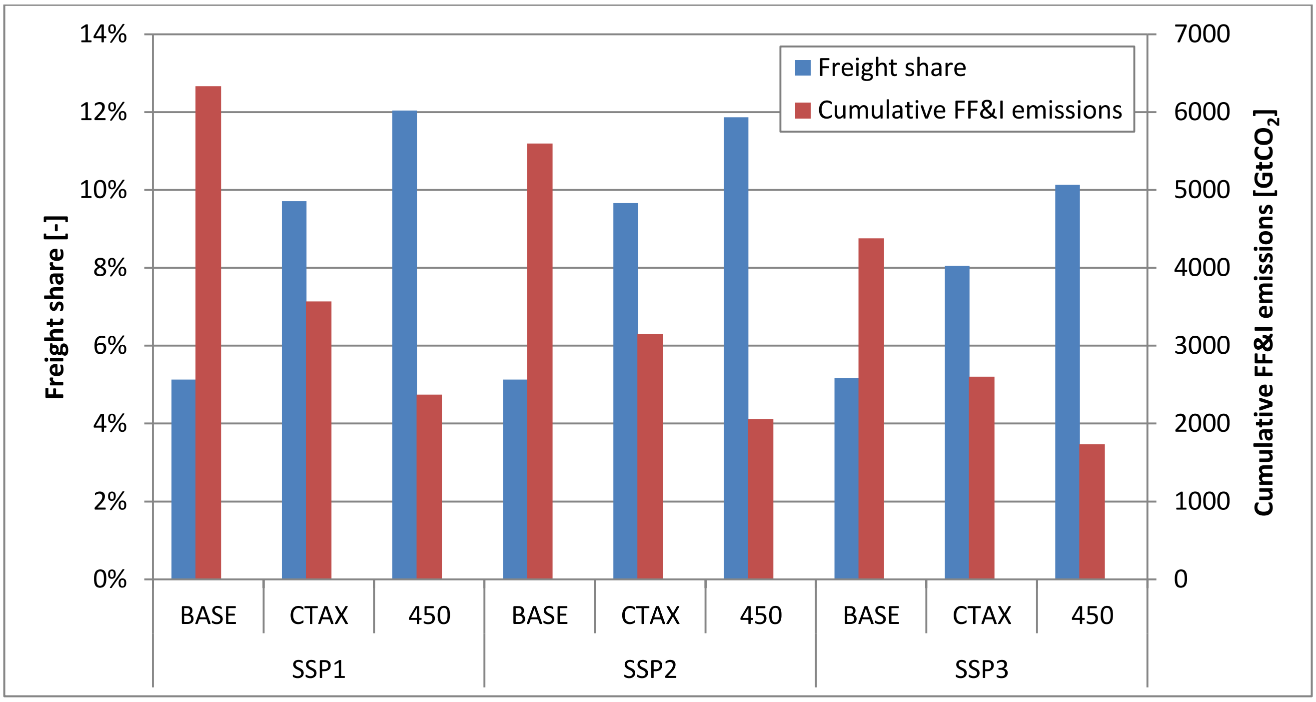
[10] Note that according to the IEA (2007), carbon dioxide emissions from the whole transport sector accounted for about one fifth of the total.

the mitigation cases is interesting as CTAX has 56-60% of the cumulative emissions of the BASE case, while 37-40% is found for the 450 scenario.

When focusing on the share of carbon dioxide emissions from the road freight sector, an interesting behaviour occurs. In all SSP scenarios the share of freight emissions with respect to FF&I emissions is lowest in the BASE cases (about 5%), intermediate in the CTAX cases (10% for SSP1-2, 8% for SSP3) and highest in the 450 scenarios (12% for SSP1-2, 10% for SSP3). This means that the decarbonisation rate of the freight sector in the mitigation policies is lower than the rate observed for the total economy. Decarbonisation in the freight sector, according to the WITCH model, contributes to carbon mitigation to a lesser extent than the other sectors. Figure 8 (right) clearly explains the cause as even in the 450 scenario, emission mitigation does not start before 2060. Then the transition that occurs is rapid, but insufficient to produce remarkable results in cumulative terms.

Figure 9. Share of road freight cumulative CO_2 emissions (left axis) and cumulative CO_2 emissions from the fossil fuels & industry sector (right axis).



It should be noted that a similar result holds for the road passenger sector as well. In the BASE scenarios the share of the cumulative emissions from this sector over the total FF&I ones is 6-7%, which grows to 10-11% in the CTAX cases and to 14-15% in the 450 scenarios. Note that in 2005 LDVs accounted for about 10% of the total FF&I emissions. Thus the finding that road freight is associated with lower decarbonisation than the rest of the economy can be extended to the entire road sector[11]. This is concordance with the findings of Pietzcker et al. (2013) and Sims et al. (2014).

At this point, it is important to detail how this decarbonisation takes place. As mentioned above, the transition towards a low-carbon freight sector is based both on the change in the fleet composition (i.e. gradually phasing out traditional combustion engines, substituted by hybrid, plug-in hybrid and electric drive

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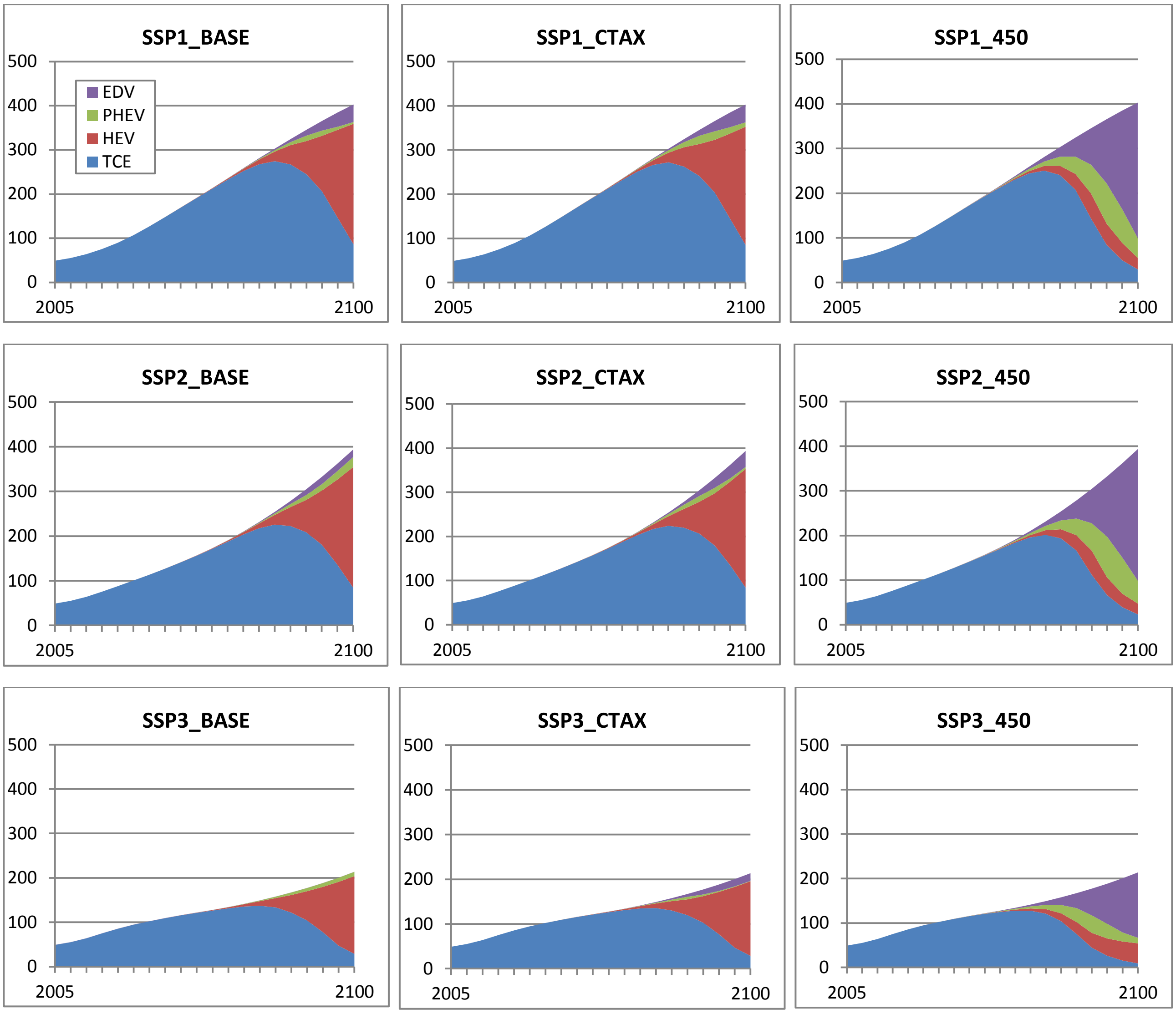
[11] Note that the road passenger sector is limited to LDVs in WITCH, but this represents a large share of road passenger emissions.

vehicles) and with the substitution of oil with biofuels in combustion engines installed on TCEs, HEVs, and PHEVs.

Figure 10 shows the fleet composition in the nine scenarios analysed.

Figure 10. Road freight global fleet composition (million vehicles).



A clear and consistent vehicle switching behaviour is visible in all scenarios as influenced by the GDP and mitigation policy settings. Traditional combustion engine vehicles dominate the market until 2060-2070, when they start being rapidly phased out. It is interesting to note that, under all SSP conditions, both in the BASE and in the CTAX cases the market becomes dominated by hybrid vehicles, while electric drive vehicles become predominant only in the most extreme decarbonisation scenarios. This means that it is not sufficient to simply implement a carbon policy to stimulate the diffusion of electric freight vehicles, but there exists a threshold below which the carbon tax does not lead to a notable electrification of this sector. Note that electrification of freight occurs in the latter part of the century and assumes that a shift towards medium sized freight vehicles occurs as part of an efficient design of a network of freight distribution centres. Transformation to urban supply chains have been happening or proposed in recent times due to motives related to decreasing the number of freight vehicles entering town centres and replacing them with a lower number of low emission vehicles or encouraging intermodal freight (Winebrake et al., 2008; Halldórsson and Kovács, 2010; Edwards et al., 2010; Österle et al., 2015). Changes to the structure of the freight system are likely to be important at a local level, but unless the climate target is stringent then it is unlikely that carbon prices that prevail for low or moderate targets will stimulate notable decarbonisation in the freight sector at the global level. It should be noted that while the European Commission has a target for all freight movements over distances greater than 300 km to be transported using rail or waterborne modes by 2030 (Tavasszy and Meijeren, 2011; EC, 2013; Sims et al., 2014) we have not considered shifts in modal shares and have fixed demands for road freight transport.

The diffusion of EDVs explains the shape of freight emissions shown in Figure 8. It should be noted that this figure does consider both direct and indirect emissions, i.e. those produced by internal combustion engines installed on TCEs, HEVs and PHEVs (direct) and those produced by the power generation plants generating the electricity used to feed PHEVs and EDVs (indirect). For the latter, the average emission factor of the entire generation fleet is adopted[12], and in this sense it must be noted that the strong decarbonisation imposed by the 450 scenario leads to a power generation sector that towards the end of the century is dominated by renewables, nuclear and CCS, i.e. carbon-free or low-carbon technologies. This means that it is possible to roughly assume that road freight electric vehicles do not imply carbon dioxide emissions (except for the fuel consumption of the internal combustion engine part of PHEVs).

In order to assess the emissions from internal combustion engines, it is necessary to analyse the share of oil and biofuels in TCEs, HEVs and PHEVs. In WITCH two kinds of biofuels are considered: traditional and advanced biofuels. Traditional biofuels are traditional ethanol and biodiesel currently adopted in existing vehicles. As for biomass in general, traditional biofuels are not supposed to produce direct emissions, as the natural resource is hypothesised to be planted again once it has been harvested, while indirect emissions due to collection, transport, etc. are taken into consideration. Therefore they are not fully carbon-free technologies. Advanced biofuels, instead, are a future breakthrough and “ideal” technology which does not generate CO_2 emissions, but requires strong R&D investments before achieving economic competitiveness and penetration of the market (see Emmerling et al., 2016, for details on the relevant technical change modelling in WITCH). In this work, however, the two types of biofuels are considered together.

Figure 11 shows the final energy of the road freight sector and considers oil, biofuels and also electricity in order to illustrate the order of magnitude of energy consumption from the different fuels or energy carriers. Oil clearly dominates the fuel portfolio in all scenarios. Thus, not only do traditional combustion engines represent the dominant technology in the generation fleet for the next fifty years, but according to WITCH estimates biofuels are not able to penetrate the fuel market to (at least partially) decarbonise it. In the SSP1 and SSP2 cases, biofuels are characterised by a higher expansion in the BASE scenarios with respect to the CTAX scenarios, which leads to a higher level of emissions in the latter scenario as previously discussed. The reason is that the mitigation policy drives energy supply towards biomass, which becomes more expensive. In the CTAX scenario, the carbon tax penalisation for oil is lower than this cost increase, and so the model chooses, at first glance somewhat counter-intuitively, to return to oil. It is finally interesting to note that electric vehicles dominate the market in 2100 in all the three 450 scenarios, but the level of final energy is not so different from oil and/or biofuel demand. This happens because the specific energy consumption of electric vehicles is far lower than that of internal combustion engine vehicles, as described in Section 2. This is hardly visible in the BASE and CTAX scenarios, because the penetration of PHEVs and EDVs, as shown in Figure 10, is practically negligible.

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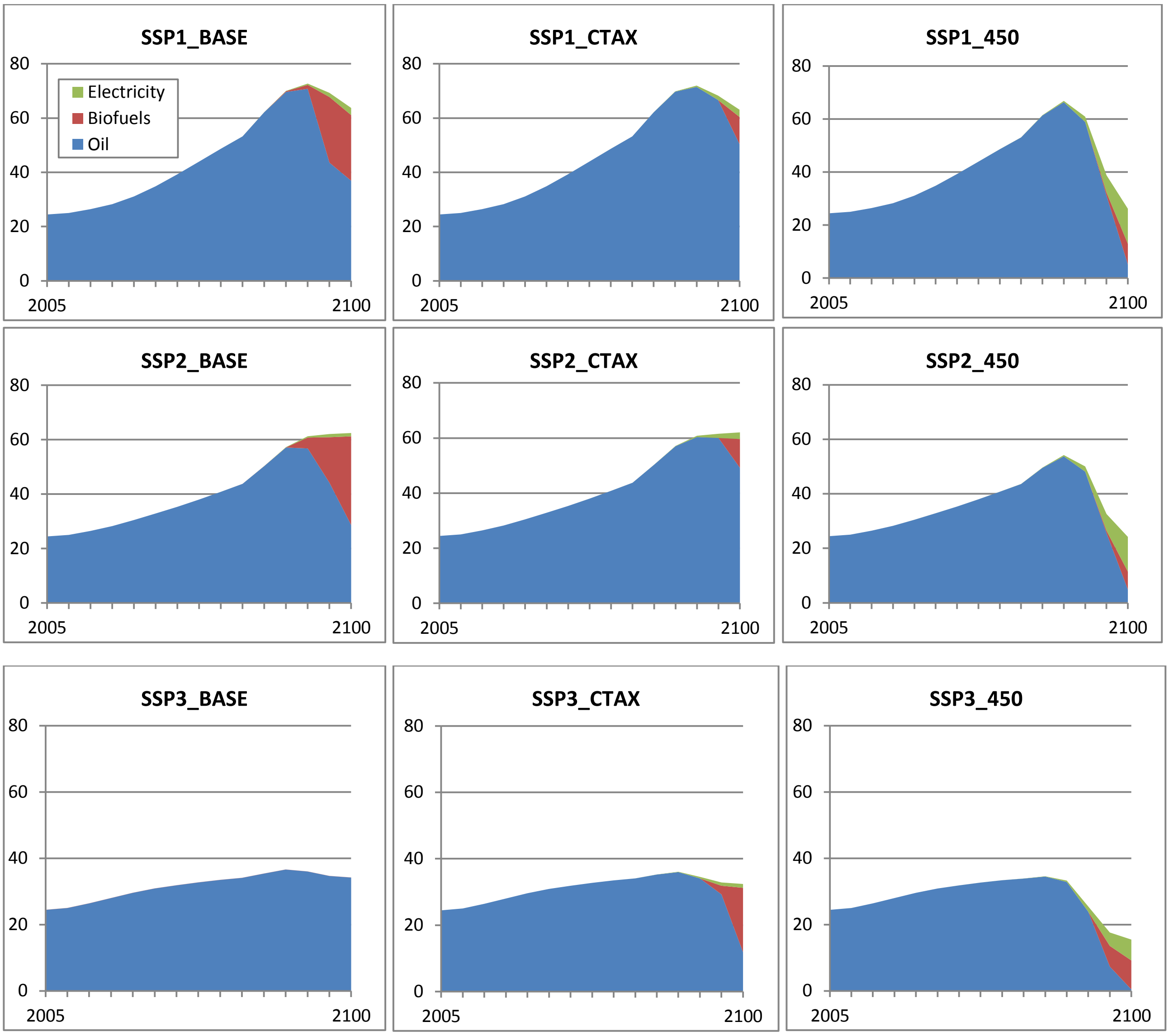
[12] It is in general impossible to track the specific power plant where the electricity consumed has been produced.

Figure 11. Road freight global final energy per fuel (EJ/yr).



6. Conclusions

Within this paper we have outlined the revision of the WITCH model to include road freight as a challenge to the decarbonisation of the global economy and the achievement of the climate policy goal of a 2°C global temperature increase. In addition to outlining the modelling approach used we have evaluated the derived road freight intensity assumptions that have been used to develop projections for the sector under different economic and climate policy scenarios using historical data from an unbalanced dataset of 62 countries between 1990 and 2010. We have also conducted analysis of the importance of road freight using three different economic growth paths and climate policies.

Overall, our results show that road freight is a challenge for the decarbonisation of the global economy, but that limited avenues for decarbonisation means that other sectors will have to compensate and decarbonise to a greater degree to achieve the range of climate policy targets we have assessed. Specifically, our results show that the current trend of a road freight sector dominated by traditional combustions engine (TCE) vehicles fed by oil products is likely to continue in the coming decades even in the presence of a strong mitigation policy. Only between 2060 and 2070 does a transition in vehicle composition start to take place. If no policy or a moderate climate policy is implemented, then TCE vehicles are mainly substituted by hybrid trucks (HEVs), while in the presence of a strong carbon policy consistent with the goal of a 2°C increase, the transition leads to a road freight fleet dominated by electric drive vehicles (EDVs). For this to occur, notable breakthroughs in battery technologies need to occur by the year 2060 and changes to freight networks towards decentralised systems of freight distribution centres is hypothesised to help this take place.

A similar rigidity in the transition in the fuel mix within combustion engines is also found as oil dominates the market and the penetration of biofuels remains limited in all scenarios. Results in terms of emissions are such that the share of carbon dioxide emissions from the freight sector over the total of fossil fuels & industry increases with the mitigation stringency, since the road freight sector is not able to decarbonise (at least in an economic efficient way) at the same pace required by the economy as a whole. These results confirm what has been found in previous literature, i.e. the road freight sector is very difficult to decarbonise and a substantial transition is likely to take place only in the second part of the century. And while the expansion of the sector is related to GDP growth, the different scenarios analysed do not show particular sensitivity within this dimension in terms of fleet composition and fuel mix. Indeed, it seems that the stringency of climate target and the decarbonisation that occurs in other sectors is more important.

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