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Deviations in Kilometres Travelled: The Impact of Different Mobility Futures on Energy Use and Climate

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Summary

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Keywords: Light Duty Vehicles, Transportation, Mobility, Climate Change Policy, Electric Drive Vehicles, Research and Development

JEL Classification: Q54, R41, O3

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September 2012

Abstract

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Section 1 – Introduction

Transportation is a sector that has shown little evidence of decoupling emissions from population and economic growth. Demand for mobility and a continued reliance on fossil fuels are amongst the reasons that this has prevailed (Knowles, 2006, Gray et al, 2006 and Frändberg & Vilhelmson, 2011). Mobility demand (in terms of vehicle kilometres travelled) has been found to be relatively inelastic with respect to changes in the cost of travel due to the value of the activity at the destination and tends to increase in cases of improved infrastructure (Metz, 2008). The persistence of mobility demand can be seen in recent trends across sectors. For example, in the period between 1980 and 2009 per capita emissions associated with manufacturing industries and construction decreased globally by 19%, while per capita emissions related to the transport sector rose by 17%. Focusing on per capita emissions associated with road transport shows an increase of 29.5% for the same period. While similar trends persist for the OECD, data for the non-OECD shows increases in per capita emissions of 14%, 63% and 95% for these same sectors (IEA, 2010). In the case of the USA, a 17% increase in per capita emissions related to road transport between 1980 and 2005 (IEA, 2010) has coincided with an increase in vehicle kilometres of 28% and a 29% improvement in fuel efficiency for light duty vehicles, buses, trucks and motorcycles (BTS, 2012). It is on this basis that a review of travel scenarios focusing on the amount of kilometres travelled has been conducted using the integrated assessment model, WITCH (Bosetti et al, 2006; Bosetti, Massetti and Tavoni, 2007; Bosetti et al, 2009; Bosetti and Longden, 2012). The application of the WITCH model allows for a review of how changes in travel patterns may impact innovations related to alternative transport options, the demand for fuels and total emissions across macro-economic regions.

The importance of a focus on mobility and fuel use attributed to light duty vehicles is reflected in the persistence of stable travel trends and strong demand for personal mobility. In accordance with this, the report titled 'Transport Outlook 2012: Seamless Transport for Greener Growth' and produced by the OECD and ITF noted that within modelling for the period between 2010 and 2050 "passenger mobility in the OECD is dominated by light-duty vehicles (cars and light trucks), and this dominance declines only to the extent that air travel takes up a greater share of total passenger-km". (OECD/ITF (2012): 20) The IEA Mo Mo model forecasts that the 2050 level of total kilometres driven by light duty vehicles will be 1.4 times higher than the 2005 level for the OECD, 7.4 times higher for the non-OECD and 2.5 times higher at the global level (Fulton et al, 2009). As prelude to the results of this paper, a constant vehicle kilometre scenario within the WITCH model closely matches the results of the IEA Mo Mo model with the 2050 level of total kilometres being estimated at a level that is 1.5 times higher than the 2005 figure for the OECD, 7.5 times higher for the non-OECD and 2.7 times higher globally.

The assumption of constant travel patterns has been used in a range of models, including the WITCH model where up until now travel patterns over time have remained fixed based on constant kilometres travelled per year (for details refer to Bosetti & Longden (2012)). Focusing on light duty vehicle travel per year, this paper makes allowance for changes in the amount of kilometres travelled based on prevailing travel patterns. Upon developing scenarios that are realistic when compared to historical trends, this paper shows that deviations in travel patterns do have a notable impact on the profile of the fleet and that investments in electric drive vehicles are important in achieving cost effective emissions abatement. In the case where carbon abatement does occur, there is a notable trend towards alternative vehicles even in a case where moderate policy takes place. A global effort to achieve a 450ppm CO2-eq concentration of GHGs by 2100 (consistent with the target of constraining temperature in 2100 to a 2ºC increase above pre-industrial levels) results in a situation where heavy investment in battery related technology occurs in the short to medium future so that plug-in hybrid electric drive vehicles become the dominant vehicle type between 2020 and 2030[1].

Section 2 reviews historical travel trends in a range of countries and then establishes scenarios for review within the WITCH model. Section 3 then focuses on the modelling of long term projections within the WITCH model and section 4 reviews simulations of a range of mobility and policy scenarios at the global level. Section 5 then concludes the paper with a discussion of the main results. Amongst other contributions, the paper will conclude that deviations in travel patterns do make a notable contribution to the profile of the fleet and that investments in electric drive vehicles are important in achieving cost effective emissions abatement, especially when mobility increases at trends consistent with historical observations.

[1] It should be noted that within the model there is no allowance for different income distributions and that the model is aimed at the macro-level. This means that cost-minimisation results in vehicle distributions that reflect the most commercially viable options and the emergence of fringe vehicles are not captured. This model also assumes that alternative vehicle types only enter when they are near perfect substitutes in cost as well as other attributes that may impact consumer preferences such as speed, power, range and refuelling demands.

Section 2 – Analysis of Travel Trends

Regular travel patterns across countries, cities and cultures have been observed and attributed to stable travel time budgets and travel money budgets. With such consistency, travel patterns and characteristics are more easily modelled and transferable across cases. In 1982 Yacov Zahavi reviewed whether the development of transport models could utilise travel characteristics that are generally transferable and consistent based on key factors at an aggregate level. Zahavi (1982) focused on the regularity of daily travel time expenditures per traveller and whether a model built with this foundation is more transferable than one which focuses on something more irregular, such as trip-rates. Within the paper, Zahavi was careful to note that there is heterogeneity in daily travel times due to differences in socio-economic groups and other factors such as mode of travel. What Zahavi wanted to establish was "whether regularities exist at a useful level of disaggregation that are transferable in space and time" (Zahavi (1982): 206). This transferability has been utilised by Schafer and Victor (2000) to project total mobility for eleven aggregate world regions up until 2050. Upon discussing travel time budgets they noted that time use surveys and travel surveys tend to show travel time budgets of approximately 1.1hrs per person per day (Schafer and Victor (2000): 174). Consistent travel money budgets were also discussed and it was noted that travel money budgets have oscillated between 7.9% and 9.0% of income (as defined by GDP per capita).

Speed and distance are factors in the amount of time used for travel and depend on the mode of vehicle and living arrangements. This led Schafer and Victor (2000) to contend that future mobility will include more extreme travel behaviour and commuting between different cities or local areas utilising high-speed transport options. These are factors that transport models and IAMs need to contend with as consistent travel time budgets and travel money budgets may imply a range of transport dynamics and differing travel modes. Metz (2010) discusses the consistency of average travel time and the lack of evidence for travel time savings from improved infrastructure. In summary, Metz (2010) notes that an "improvement in the transport system allows further access to desired destinations, within the more or less constant time people allow themselves on average for travel" (Metz (2010): 333). Millard-Ball and Schipper (2010) raise the issue of saturation for both vehicle ownership and travel; noting that unless travel speeds increase ever-rising travel activity will likely be constrained through the impact of travel budgets. Further to this, the authors note that while their results are not conclusive, they "can be seen as a challenge to travel demand and energy models that project continued rises in VMT". (Millard-Ball & Schipper, 2010: 3)

Having established a model for transportation in Bosetti & Longden (2012) this review is the first stage of a process of additional development of the model and an attempt to investigate and incorporate additional issues, such as changes in travel patterns. Having established that travel patterns at the national level do show signs of stability over an extended period and that they are indeed an important consideration, the review will now turn to travel scenarios and how adequately they reflect historical data. Table 1 defines seven travel scenarios that will be applied within the WITCH model and reviewed in section 4. A growth rate of 1.2% per annum has been selected as the point of reference as it matches the growth of the average number of miles travelled by automobiles that was directly associated with an increase in distance travelled for the USA between 1985 and 2005. (US EPA, 2010) Note that the overall increase in VKMs travelled in the period was approximately 1.5% per annum; however 0.3% was attributed to growth in the number of vehicles registered. In line with the investigation and concerns of Millard-Ball and Schipper (2010), these scenarios include both increasing and decreasing mobility trends. Within Figure 1 and Figure 2, a review of historical travel patterns across countries from the OECD and non-OECD shows that these mobility scenarios are generally consistent with past trends that correspond with national level data from the International Transport Forum (accessed via OECD Stat).

Table 1. Description of Travel Scenarios

Scenario Name and Acronym	*Brief Description*
Constant VKM (Scen1)	No increase in kilometres driven per vehicle
Increase VKM – 0.6% per annum (Scen2)	Slight annual increase in kilometres driven per vehicle
Increase VKM – 1.2% per annum (Scen3)	Moderate annual increase in kilometres driven per vehicle
Increase VKM – 1.8% per annum (Scen4)	Large annual increase in kilometres driven per vehicle
Decrease VKM – 0.6% per annum (Scen5)	Slight annual decrease in kilometres driven per vehicle
Decrease VKM – 1.2% per annum (Scen6)	Moderate annual decrease in kilometres driven per vehicle
Decrease VKM – 1.8% per annum (Scen7)	Large annual decrease in kilometres driven per vehicle

Upon reviewing Figure 1, there is a comparison of the estimates from the WITCH model with the ITF data in terms of passenger kilometres (PKM) per 1000 persons. The progression of scenario one between 2005 and 2045 is slightly conservative in comparison to the World average level of PKM per 1000 persons between 1970 and 2010. Scenario two matches the World average level quite well, while scenario three and four tend to growth a bit faster than this historical average. The square points for 2005 and 2010 show the global, OECD and non-OECD averages that are inferred within the WITCH model for these initial periods. Note that a direct comparison of these initial periods needs to account for missing data in the non-OECD, as reflected in the sensitivity of the non-OECD Average to additional countries in the dataset after 2001. Some countries of interest have been highlighted using different colours, with notable differences in the growth of mobility within the OECD – as reflected in the difference between a stable level for the United States and notable growth in Italy, Germany and France. Figure 2 reviews national trends between 2005 and 2010 in terms of the percentage change in PKMs in comparison to 2005. Focusing on PKMs results in a clear distinction between the trends within the OECD and the non-OECD with some countries of interest again highlighted using different colours.

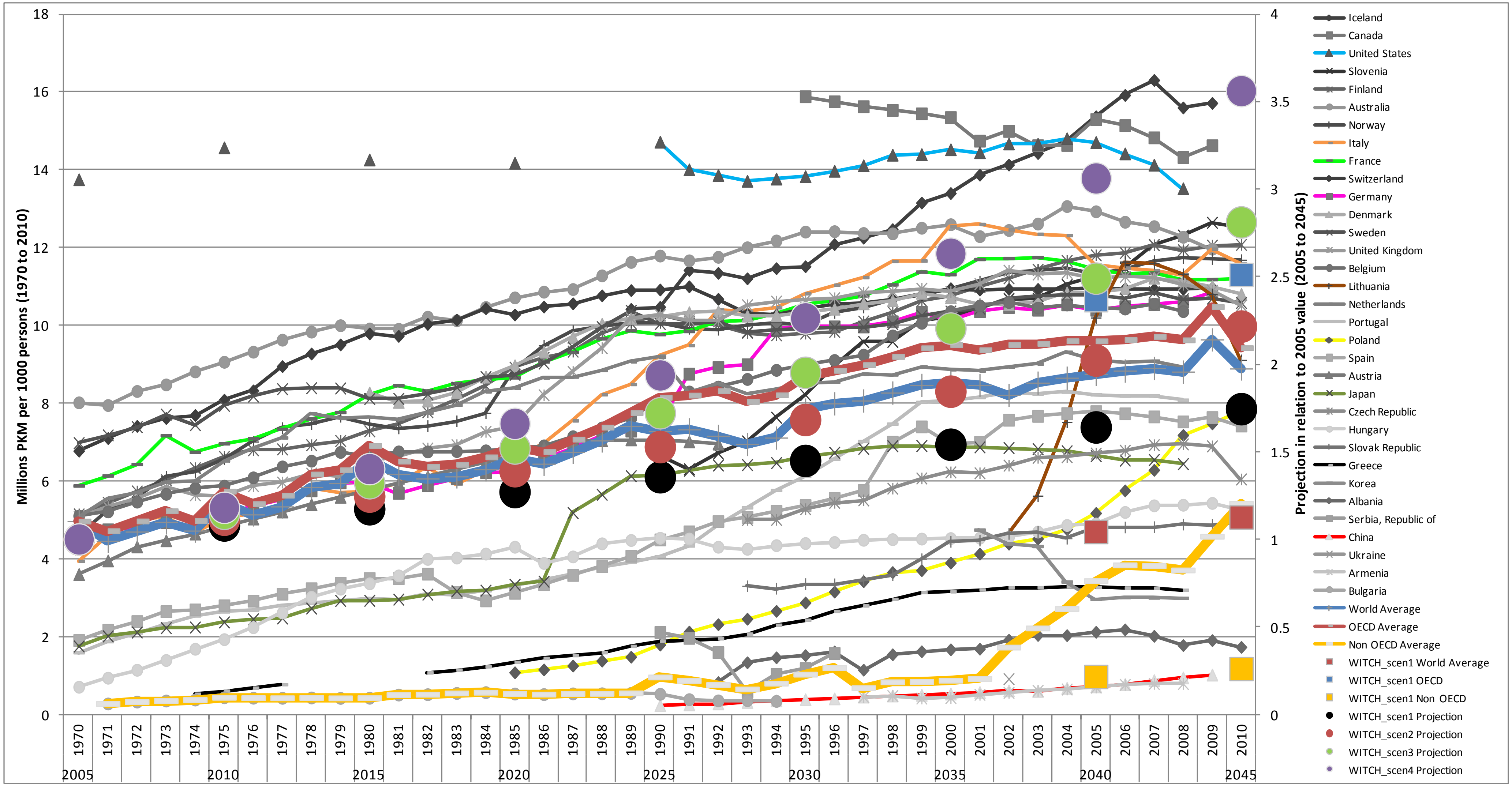
Mobility growth in China between 2005 and 2009 significantly dwarfs the stable or decreasing trends seen within certain European countries, Australia and the United States. In the case of China, mobility growth has increased considerably since 1990 with the 2009 level of PKM being 5 times higher than the 1990 level[2]. In the United States growth after 1990 led to a level of PKM in 2008 that is 1.12 times higher than the 1990 level. Observations for the US during the same period oscillated between a low of 96% the 1990 level (in 1991) and a high of 118% the 1990 level (in 2005). Growth in some European countries has been increasing steadily since 1990 with the level of PKM in Germany, Italy and France being 1.5, 1.4 and 1.3 times higher than the 1990 level in 2009. In summary, the compound annual growth rate implied by these figures sourced from the ITF are 8.5% for China, 0.6% for the United States, 2.0% for Germany, 1.6% for Italy and 1.2% for France. By utilising the two most conservative increased mobility scenarios within Table 1 we replicate growth rates that are similar to those that have existed within the OECD for the periods reviewed. While scenario three and four increase at a rate higher than the historical growth of many OECD countries, they are relatively conservative in comparison to the growth seen in China and Poland. Adjusting the values in Table 1 for direct comparison with these estimates results in the compound annual growth rate for PKMs for scenario one being 1.6%, 2.2% for scenario two, 2.8% for scenario three and 3.4% for scenario four.

The level and persistence of growth within the non-OECD at this point in time is an open question due to the lack of historical data for many important countries (other than China) and concerns that extrapolating the growth seen in some countries in the recent past will likely be inappropriate. Issues that need to be considered include demographic shifts, the scale of required infrastructure investments and saturation related to the number of vehicles per capita. In developing this paper, reviews of travel patterns have been undertaken without comprehensive results for the non-OECD. The implementation of travel elasticities based on an extension of the ‘travel elasticity switch’ specified within Fulton et al (2009) are inappropriate for the non-OECD without improved estimates for the elasticity of travel based on per capita vehicle ownership. As a result, a future extension of this paper will focus on developing mobility scenarios appropriate for the non-OECD, the incorporation of switching between

[2] Note that 1990 is the first year where the ITF data series has data for China.

transport options and incorporating endogenous travel patterns through the application of travel elasticities (with improved estimates for non-OECD regions).

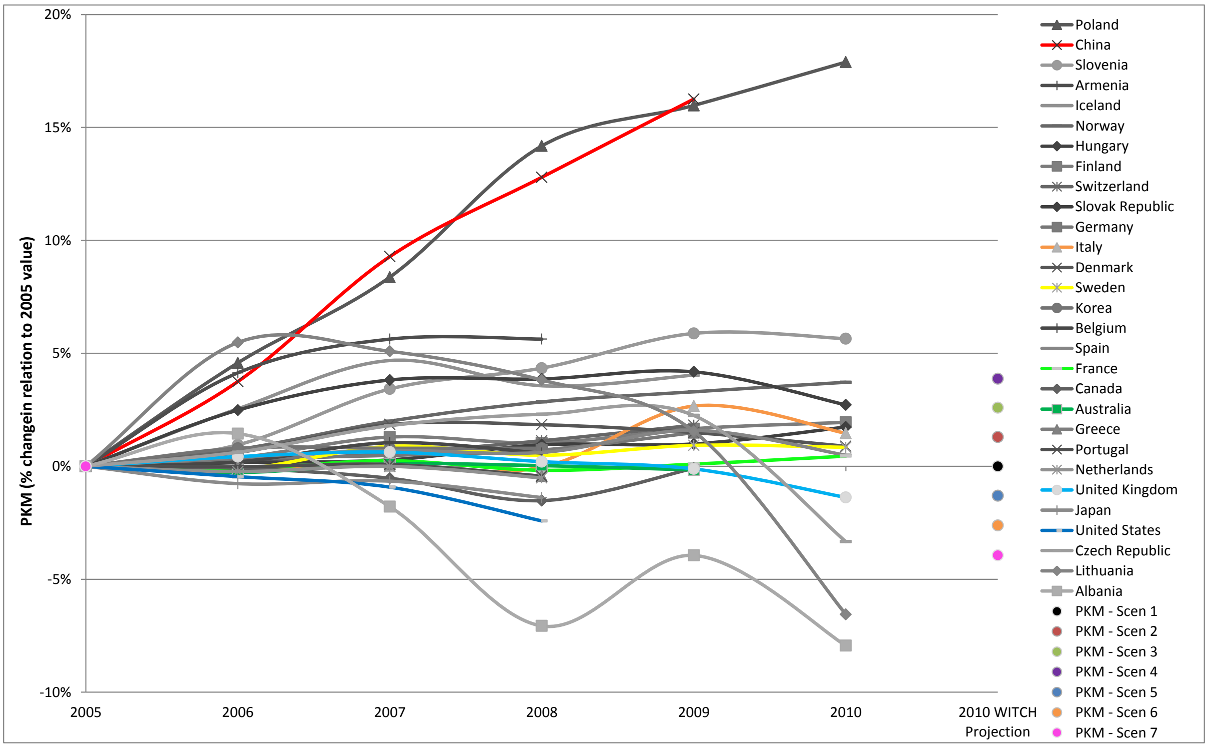
Figure 1. Passenger Kilometres per 1000 persons – Review of WITCH Scenario Projections and Historical Data.



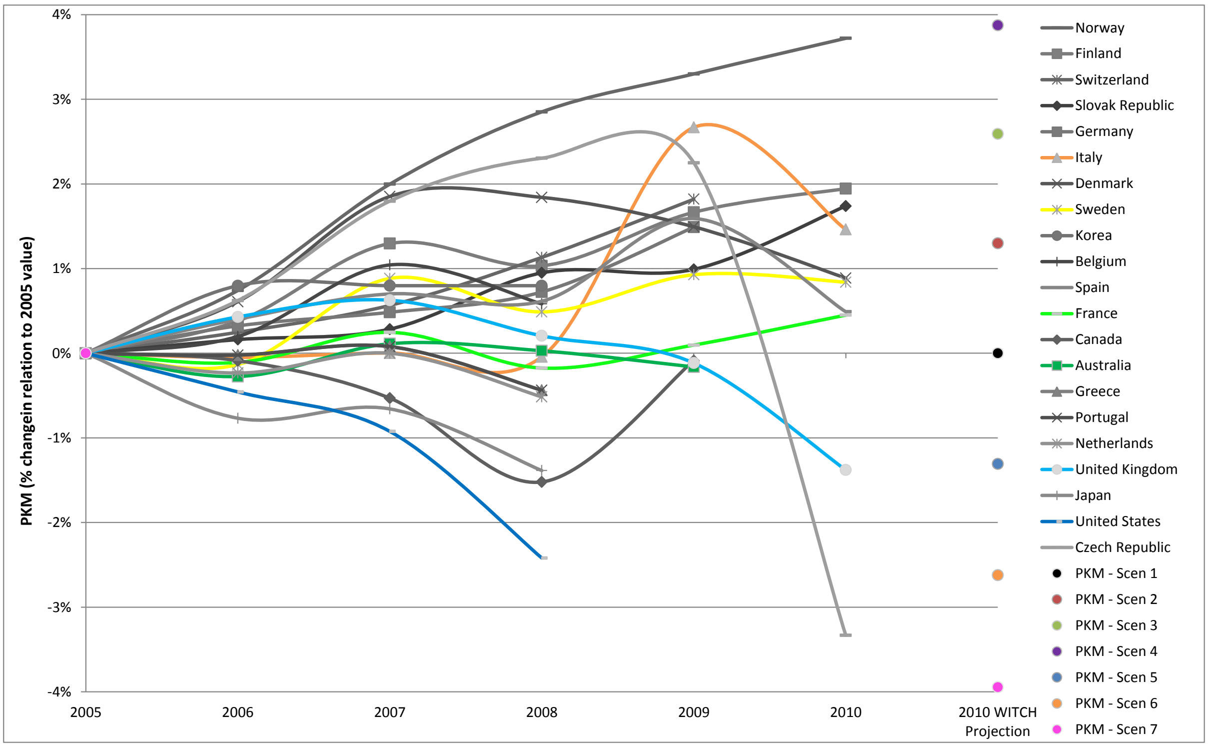
Note: data points using the 1970-2010 time scale consist of the historical line plots and the WITCH model averages for 2005 and 2010. The dot plots that coincide with the WITCH model projections (last four labels in the legend) use the 2005-2045 time scale and the right vertical axis. In the case of the historical line plots, the legend labels appear in order of the last observation.

Figure 2. Passenger Kilometres – Review of WITCH Scenario Projections and Historical Data.

All Countries – OECD and non-OECD



Limited Range of Countries – OECD



Note: the last seven labels in the legend refer to the estimates sourced from the WITCH model. In the case of the historical line plots, the legend labels appear in order of the last observation.

Table 2. Transportation Models KM Forecasts

MODELS	REGION	Billions KM 2005 Total (Ratio using 2005 value)	Billions KM 2030 Total (Ratio using 2005 value)	Billions KM 2050 Total (Ratio using 2005 value)	Billions PKM 2005 (Ratio using 2005 value)	Billions PKM 2030 (Ratio using 2005 value)	Billions PKM 2050 (Ratio using 2005 value)	TIME PERIOD COVERED	REFERENCE
IEA/SMP	OECD	8,181 (1.0)	10,600 (1.3)	11,679 (1.4)	12,753 (1.0)	15,311 (1.2)	16,184 (1.3)	2000-2050	*Fulton, L. and Eads, G. (2004)*
	Non OECD	1,975 (1.0)	6,040 (3.1)	12,755 (6.5)	3,546 (1.0)	9,856 (2.8)	19,688 (5.6)		
	Global	**10,156 (1.0)**	**16640 (1.6)**	**24,434 (2.4)**	**16,299 (1.0)**	**25,167 (1.5)**	**35,873 (2.2)**		
IEA MoMo – reference case	OECD	8,880 (1.0)	11,455 (1.3)	12,539 (1.4)	13,850 (1.0)	16,582 (1.2)	17,420 (1.3)	2005-2050	*Fulton, L. et al (2009)*
	Non OECD	2,065 (1.0)	7,204 (3.5)	15,326 (7.4)	3,713 (1.0)	11,864 (3.2)	23,850 (6.4)		
	Global	**10,945 (1.0)**	**18,659 (1.7)**	**27,866 (2.5)**	**17,563 (1.0)**	**28,446 (1.6)**	**41,270 (2.3)**		
WITCH – Scen1	OECD	8,527 (1.0)	11,246 (1.3)	12,776 (1.5)	13,362 (1.0)	17,639 (1.3)	20,015 (1.5)	2005-2100	
	Non OECD	2,185 (1.0)	8466 (3.9)	16,447 (7.5)	3,902 (1.0)	15,217 (3.9)	29,684 (7.6)		
	Global	**10,712 (1.0)**	**19,713 (1.8)**	**29,223 (2.7)**	**17,264 (1.0)**	**32,855 (1.9)**	**49,699 (2.9)**		
WITCH – Scen2	OECD	8,527 (1.0)	13,061 (1.5)	16,723 (2.0)	13,362 (1.0)	20,484 (1.5)	26,198 (2.0)	2005-2100	
	Non OECD	2,185 (1.0)	9,832 (4.5)	21,528 (9.9)	3,902 (1.0)	17,671 (4.5)	38,854 (10.0)		
	Global	**10,712 (1.0)**	**22,893 (2.1)**	**38,251 (3.6)**	**17,264 (1.0)**	**38,155 (2.2)**	**65,052 (3.8)**		
WITCH – Scen5	OECD	8,527 (1.0)	9,676 (1.1)	9,745 (1.1)	13,362 (1.0)	15,175 (1.1)	15,267 (1.1)	2005-2100	
	Non OECD	2,185 (1.0)	7,284 (3.3)	12,545 (5.7)	3,902 (1.0)	13,091 (3.4)	22,642 (5.8)		
	Global	**10,712 (1.0)**	**16,959 (1.6)**	**22,290 (2.1)**	**17,264 (1.0)**	**28,266 (1.6)**	**37,908 (2.2)**		

Table 2 compares the model's estimations for future mobility growth across three of the vehicle kilometre (VKM) scenarios and two models developed by the IEA. In terms of total KM travelled, the WITCH model (applying scenario one) closely matches the IEA models at the OECD level in all periods. Some small divergence at the global level exists but this tends to occur within a comparison to the IEA/SMP model and is due to differing vehicle fleet estimates for the non-OECD. Reviewing the PKM numbers across models shows the sensitivity of PKM variable to the estimate of the number of vehicles. Table 3 reviews the number of vehicles for each of the models included within Table 2. The WITCH model estimates related to the number of vehicles in the OECD and non-OECD are in line with the IEA/SMP model and the 'Reference Case' scenario presented for the IEA Mo Mo model. The global projections of the two IEA models are slightly more conservative than that of the WITCH model with the 2050 global vehicle ownership being 2.7 or 2.9 times higher than the 2005 level and this is primarily due to differences in the growth seen within non-OECD countries. Within the models the relationship between vehicle kilometres and passenger kilometres is held constant as the average number of passengers in the baseline period is applied in all other periods. The WITCH model applies that same average number of passengers as that of the IEA/SMP model with some adjustment for regional specifications.

Table 3. Transportation Models Vehicle Forecasts

MODELS	REGION	Millions LDVs 2005 No. (Ratio using 2005 value)	Millions LDVs 2030 No. (Ratio using 2005 value)	Millions LDVs 2050 No. (Ratio using 2005 value)	GLOBAL / REGIONAL FOCUS	FORECAST TIMELINE	REFERENCE
IEA/SMP	OECD	565.8 (1.00)	727.7 (1.29)	792.5 (1.40)	Global and Regional	2000 - 2050	*Fulton, L. and Eads, G. (2004)*
	Non-OECD	178.5 (1.00)	560.9 (3.14)	1216.9 (6.82)			
	Global	**744.3 (1.00)**	**1288.6 (1.73)**	**2009.4 (2.70)**			
IEA MoMo – reference case	OECD	576.0 (1.00)	748.0 (1.30)	813.0 (1.41)	Global and Regional	2005 - 2050	*Fulton, L. et al (2009)*
	Non-OECD	173.0 (1.00)	618.0 (3.57)	1331.0 (7.69)			
	Global	**749.0 (1.00)**	**1367.0 (1.83)**	**2144.0 (2.86)**			
WITCH – all scenarios	OECD	542.2 (1.00)	713.6 (1.32)	804.6 (1.48)	Global and Regional	2005 - 2100	
	Non-OECD	188.5 (1.00)	759.5 (4.03)	1521.7 (8.07)			
	Global	**730.7(1.00)**	**1473.2 (2.02)**	**2326.3 (3.18)**			

Section 3 – Modelling long term transportation projections

Other than reviewing travel behaviours and estimates for kilometres travelled, this paper will also utilise an integrated assessment model to provide the basis for macro-level simulations of differences in transport scenarios. WITCH – World Induced Technical Change Hybrid model – is a regional integrated assessment model that provides normative information on the optimal responses of world economies to climate policies. Recent work has been conducted to expand the model to include a light duty vehicle (LDV) transport sector and provide representations of the future of personal travel. Details of the WITCH model and the inclusion of LDV transport can be found in Bosetti and Longden (2012). The model incorporates representations of traditional combustion engine (TCE) vehicles, traditional hybrid (HYBRID) vehicles, traditional biofuel (BIOFUEL) vehicles, advanced biofuel (ADV BIOFUEL) vehicles, plug-in hybrid electric drive vehicles (PHEVs) and electric drive vehicles (EDVs). With respect to climate policies, the model combines sectorial analysis of the World economy with a climate module and CO_2 emission restrictions. Within this paper a "cost-minimisation" approach will be used which excludes the use of the damage function that provides climate feedback on the economic system. The model directly incorporates CO_2 emissions but not other GHGs, whose concentration is added exogenously to the CO_2 concentration to obtain the overall GHG concentration. Within this approach, a 450ppm CO_2 concentration scenario is roughly assumed to correspond to a 550ppm overall GHG concentration scenario in the stabilisation scenario simulations following. The 550ppm GHG scenario coincides with a target of a 2.5ºC temperature increase above pre-industrial levels at 2100. A 550ppm and a 450ppm scenario (which coincides with a target of a 2 ºC temperature increase above pre-industrial levels at 2100) will be applied with Section 4.

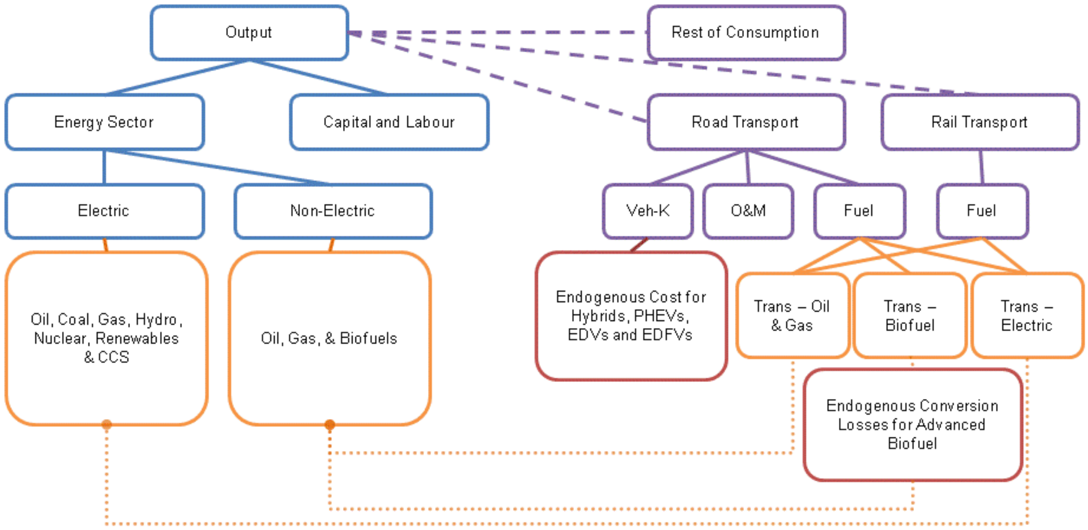
A dynamic optimal growth general equilibrium model, WITCH has a detailed ('bottom-up') representation of the energy sector and a light duty vehicle transport sector. Belonging to the class of hybrid (both 'top-down' and 'bottom-up') models, the top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been integrated into a bottom-up representation of the energy sector. WITCH's top-down framework guarantees a coherent, fully intertemporal allocation of investments, including those in the energy sector and the transport sector. Divided into 13 macro-regions it is a global model with regional representation[3]. The base year for calibration is 2005 and all monetary values are in constant 2005

[3] The regions are USA, WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (South Korea, South Africa and Australia), CAJANZ (Canada, Japan and New Zealand), TE (Transition Economies), MENA (Middle East and South Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), SEASIA (South-East Asia), CHINA, LACA (Latin America and the Caribbean), and INDIA.

USD. The WITCH model uses market exchange rates for international income comparisons. The description which follows reviews the overall model structure and a summary on the incorporation of the LDV transport sector into the wider model.

Transport has been included in the WITCH model through the incorporation of the impact of investments in LDVs and fuel expenditures on the level of consumption. This means that increased LDV travel (in terms of kilometres travelled per vehicle) as well as the costs of the vehicle and fuel expenditure directly impact utility through the corresponding effect of decreasing consumption on other goods and services. Figure 3 shows the transportation module within the WITCH model structure. The model separates consumption in transport from the rest of consumption, which allows for the direct modelling of the costs involved in switching between vehicles and fuels for a given demand of mobility. Investments in vehicle capital and supplementary costs decrease the level of consumption. A Leontief production function (Road Transport in Figure 3) represents the fixed proportions of operation & maintenance (O&M) costs, fuel and investment cost required for each technological type. Fuel demand and fuel category depend upon the vehicle chosen. The LDV transport sector's demand for fuels (oil, gas, biofuels and electricity) compete with other energy sectors. Investments in technological advancements can be made which results in decreases in the cost of batteries used in traditional hybrids, PHEVs and EDVs. Investments can also be made to reduce the conversion losses associated with the production of biofuel from biomass. It should be noted that within the model there is no allowance for different income distributions and that the model is aimed at the macro-level. This means that cost-minimisation results in vehicle distributions that reflect the most commercially viable vehicle option and the emergence of fringe vehicles are not captured. While the focus of this paper is on the light duty vehicle component of road transport, the WITCH model does have representations of road freight and rail transport. A review of the full range of transport sectors has been left for forthcoming work.

Figure 3. The transport module



Note: transport cost is modeled as part of consumption. Biofuel consumption in the transportation sector competes with biomass use in electricity production. Demand for Oil & Gas competes with demand coming from both electric and non-electric sector. Demand for electricity coming from the transport sector has to be met by the electric component of the energy sector and can be sourced from any available option.

Having set out the general structure of the model, we will now clarify the description provided above with a review of the main equations in the model. With respect to the following equations, the complete list of variables is reported in the appendix within table 1A. In each region, indexed by n, a social planner maximises the utility function represented in equation 1. Time is reflected as t which denotes 5-year time spans and R(t) is the pure time preference discount factor.

$$W(n) = \sum_t U[C(n,t), L(n,t)] R(t) = \sum_t L(n,t) \log[c(n,t)] R(t) \qquad (1)$$

Equation 2 and 3 represent the distinction between the aggregate level of consumption, CG, and the level of consumption net of transport, C. This distinction is made as transport expenditure is modelled as a cost that is inherent within consumption activities. Expenditures on personal transport utilising both road and rail are consistent with a travel money budget and hence are treated as a cost of consumption. This implies that any increase/decrease in travel cost impacts the travel money budget and this then decreases/increases the remaining budget allocated to consumption activities. Freight costs are modelled as a cost related to consumption goods, where upon the increased/decreased cost of transportation within the region are passed on to the consumer through higher/lower prices of these consumption goods. With no trade of consumption goods between regions, freight transportation costs and demand are relatively stable and hence steadily impact the remaining budget allocated to consumption activities. CG is defined by the budget constraint represented in equation 2 where Y is output, I are investments in final good, energy technologies and R&D, and O&M represents investments in the operation and maintenance of technologies in the energy sector.

$$CG(n,t) = Y(n,t) - I_c(n,t) - \sum_j I_{R\&D,j}(n,t) - \sum_j I_j(n,t) - \sum_j O\&M_j(n,t) \quad (2)$$

The aggregate level of consumption net of transport expenses, is gross consumption subtracted by the cost for private transportation, including investments in road vehicles, I_{road}, investments in research related to battery and/or advanced biofuel conversion technologies, RI_{TECH}, operation and maintenance of the vehicles, $O\&M_{road}$, and the fuel costs, $FE_{trans,j}$, of each fuel j. Expenditure on rail, $RE_{rail,j}$, is made up of service charges for rail services that are comprised by the variable costs of the provision of rail and is set to the aggregate cost of each fuel j and operation and maintenance of the rail network. Note that the provision/scale of road and rail infrastructure networks are captured within the level of final goods that underlies the level of output in equation 2.

$$C(n,t) = CG(n,t) - \sum_{road} I_{road}(n,t) - RI_{TECH}(n,t) - \sum_{road} O\&M_{road}(n,t) - \sum_{road,j} FE_{road,j}(n,t) - \sum_{rail,j} RE_{rail,j}(n,t) \quad (3)$$

Starting with the level of investments in vehicles during time period one, equation 4 sets the subsequent period's capital stock of road vehicles, K_{road}, equal to the level of capital remaining after depreciation[4] and the additional capital implied by investments undertaken at the prevailing investment cost of vehicles, SC_{road}. The amount of capital for road transportation in each period within each region is constrained by the demand on personal mobility and freight (which are functions of GDP and other factors, such as congestion in the case of personal mobility, which is reflected by the number of vehicles per 1000 persons).

$$K_{road}(n,t+1) = (1-D)\,K_{road}(n,t) + (I_{road}(n,t)/SC_{road}(n,t)) \quad (4)$$

The amount of fuel demanded by each vehicle is defined by the average fuel efficiency of the vehicle, fuel efficiency improvement, and the amount of kilometres travelled per year. Note that the adjustment of the fuel efficiency improvement occurs in cases where the amount of kilometres travelled per year is modified. Within this model this occurs using an adjustment factor that is a function of time and the kilometres travelled in the corresponding time period. Fuel efficiency improvements are time dependent and assumptions on the dynamics are detailed within Bosetti & Longden (2012). Estimates of the amount of passengers and freight hauled per vehicle are then applied to derive passenger kilometres and tonne kilometres.

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[4] The rate of depreciation is set to reflect a replacement of vehicles occurring every 15 years. Within this version, no distinction has been made for the existence of used vehicles other than an extended first use lifetime of 15 years, rather than the 12.5 year lifetime that the model was originally built with.

The range of road vehicles, *road*, introduced into the model has been selected to give a representative overview of the type of vehicles expected to come into contention for successful market penetration in the medium to long term future. For each of these vehicle categories we have set different fuel economy and vehicle cost levels. The range of light duty vehicles included in this review consists of traditional combustion engine vehicles (TCE), hybrid vehicles (HYBRID), traditional biofuel fuelled vehicles (BIOFUEL), advanced biofuel fuelled vehicles (ADV BIOFUEL), plug-in hybrid electric drive vehicles (PHEVs) and electric drive vehicles (EDV). Freight vehicles are made up of traditional combustion diesel fuelled trucks, hybrid trucks, natural gas fuelled trucks, traditional biofuel fuelled trucks, advanced biofuel fuelled trucks, and electric drive haulage vehicles. Note that the modelling of rail has not involved the introduction of specific vehicles into the model and this component of transport is reviewed on the basis of energy used and kilometres travelled. The focus on this paper is on vehicle kilometres using light duty vehicles and the discussion following will focus on changes within the LDV transport sector. No substitution between road and rail transportation occurs within this paper, but these considerations will be investigated in future work.

Technological change is endogenous in the model and it affects both the cost of batteries for electrified vehicles and the conversion losses involved in producing biofuel from biomass. As reflected in equation 5, research capital in either of these technologies (RK_{TECH}) depreciates at a given rate of depreciation (D_K), is accumulated with increased investments ($RI_{TECH}\ n, t$), and is impacted by a ‘standing on the shoulders of giants’ effect based on the previous level of capital.

$$RK_{TECH\ n,t+1} = 1 - D_K \quad RK_{TECH\ n,t} \quad + \quad RI_{TECH\ n,t}{}^{0.85} \ * (RK_{TECH(n,t)}{}^{0.15}) \qquad (5)$$

The incentive to accumulate research capital can be seen by its role within the learning by searching curves, shown in equations 6 and 7, which improve the state of these technologies. In particular, cumulating knowledge decreases the cost of batteries used in EDVs (BC_{EDV}) [5]and decrease the cost of advanced biofuel (FE_{ADVB}) through decreased conversion losses when converting woody biomass into biofuels.

$$\frac{BC_{EDV(n,t)}}{BC_{EDV(n,1)}} = \frac{(RK_{EDV\ n,t} + RSpill_{EDV(n,t-l)}}{RK_{EDV(n,1)}}^{-LR} \qquad (6)$$

$$\frac{FE_{ADVB\ n,t}}{FE_{ADVB\ n,1}} = \frac{(RK_{ADVB\ n,t} + RSpill_{ADVB(n,t-l)}}{RK_{ADVB(n,1)}}^{-LR} \qquad (7)$$

[5] Note that the change in the price of batteries for EDVs impacts the price of tradition hybrids and PHEVs using a fixed relationship based on the difference in prices in the initial period and the assumption that these technologies follow the trends of the most concentrated form of the technology.

As spillovers are likely to occur in technologies that are easily tradable we assume that the cost in each country is affected by the research cumulated in that country up to that period and the amount of research accumulated by the sector innovation leader through spillovers, $\mathrm{RSpill}_{\mathrm{ADVB/EDV}}$. This spillover occurs with a lag time (*l*) that accounts for the advantage of being a first mover. The model assumes that the transfer of technology can occur rapidly to reflect the existence of licensing arrangements and the establishment of production factories within foreign markets through related companies. Such arrangements can be seen in the expansion of the market for the Nissan Leaf[6] and the support by the European Investment Bank to produce electric batteries at the Nissan Sunderland Plant in the UK from early 2012. (EIB, 2011) Spillovers in technology have been identified previously, such as in Schwoon (2008) where it is noted that the car industry is characterised by learning spillovers due to the prevalence of technology clusters and common sub-contractors.

[6] In 2011 Nissan extended European sales of the Nissan Leaf from the UK, the Netherlands, the Republic of Ireland, France, Spain, Switzerland and Portugal to also include Belgium, Norway, Sweden and Denmark. (EIB, 2011)

Section 4 – LDV Transport Sector Dynamics

This section reviews the sensitivity of the model to different travel assumptions under a range of policy scenarios. Described within Table 4, these policy scenarios include a 'Limited Policy' scenario which has been designed to reflect the current state of the world (without the achievement of Copenhagen policy targets). A 'Moderate Policy' scenario where in addition to increasing investments in R&D related to batteries[7], emission reduction targets and Renewable Targets for biofuels in 2020[8] are met within the USA and the EU. The last two scenarios apply two global carbon trading schemes aimed at meeting a 2.5ºC and 2ºC target, respectively[9]. The application of the 'Limited Policy' and 'Moderate Policy' scenarios are aimed at capturing the effect of some of the advances in policy and innovation that are currently underway. By utilizing WITCH we are able to simulate climate policy in an ideal environment in which all world regions agree on the stabilization target and credibly commit to achieve it. Regions receive emission allowances that can be traded in an international carbon market. Emissions from all sectors, including transportation, are capped. Banking and borrowing is allowed within the solution and hence reflects an inter-temporally optimal emissions reduction trajectory.

Limited Policy

To set a baseline for the analysis a limited policy baseline is established based on current trends without the effect of prescribed carbon abatement policies. Figure 4 and Figure 5 review the global vehicle distribution that prevails under this scenario with the different trends in mobility that were noted in section 2, Table 1. With limited carbon abatement policy applied and investments in battery technologies ceasing after 2010, the electrification of light duty vehicles at the global level tends to occur between 2050 and 2075[10] in all but the two most acutely increasing mobility scenarios. Increased mobility leads to increased fuel demand and this creates an incentive for fuel switching towards alternative fuels and hence electrification. With the renewable fuel content targets in the USA

[7] Investments in battery technologies for the USA, the EU and Japan in 2005 and 2010 have been set equal to the 'Energy Storage' totals within the RD&D Budgets accessed through the IEA Energy Technologies RD 2011 edition database. Projections for 2015 and 2020 match the growth rate between 2005 and 2010.

[8] Refer to Table 1 of the Technology Roadmap – Biofuels for Transport produced by the IEA (2011) for the Renewable Targets for biofuel blending targets and mandates. The EU has a target of 10% and the assumption applied within this study is that most of this will be sourced from biofuels. For the USA, 136 billion litres of biofuels has been computed to be close to a 20% fuel share within the light duty vehicle sector in 2020.

[9] Although this is unlikely to be the outcome of future climate negotiations, it is a useful assumption for the objective of the present analysis as there is a focus on the optimal fleet composition that is implied by these carbon targets.

[10] It should be noted that within the model there is no allowance for different income distributions and that the model is aimed at the macro-level. This means that cost-minimisation results in vehicle distributions that reflect the most commercially viable options and the emergence of fringe vehicles are not captured. This model also assumes that alternative vehicle types only enter when they are near perfect substitutes in cost as well as other attributes that may impact consumer preferences such as speed, power and refuelling demands.

and the EU being achieved, notable investments in the conversion of biofuel from biomass occur in 2010 and 2015. Within scenario 1, these investments are highest in the EU, followed by the USA, LACA and China. The global investment shares in biofuel conversion in 2015 are: the EU at 40%, the USA at 28%, LACA at 21%, China at 8% and the rest of the World at approximately 3%. The emergence of the EU as the major investor in biofuel conversion is due to the fulfilment of their renewable content target using a high level of biofuels with advanced conversion processes. Within scenario 1, advanced biofuel within the EU is approximately 75% of the overall biofuel mix, while it is only 41% in the USA due to the higher potential for biofuels from grain based ethanol. The difference across these regions is consistent with the projections within Alfstad (2008). Across the mobility scenarios this trend changes with the USA becoming the largest investor when kilometres travelled per year increases. Within the scenarios where mobility decreases, LACA tends to have an increased share of global investments and surpasses USA investments in 2015 within scenario 5, reaches EU investments within scenario 6, and surpasses EU investments in scenario 7.

Table 4. Description of Policy Scenarios

Policy Scenario Name	***Brief Description***
Limited Policy	No carbon policy is applied and the model is solved for optimal investments based on the cost of vehicles, fuel costs and no carbon cost – investments in battery technologies within the USA, the EU and Japan are set for 2005 and 2010 (with no lower bound after this) – the USA and the EU achieve their 2020 renewable targets through the use of biofuels – total abatement effort is consistent with constraining temperature in 2100 to approximately a 4.3ºC increase above pre-industrial levels.
Moderate Policy	Moderate carbon policy is applied in within the USA and the EU – by 2020 this leads to a reduction of GHG emissions of 5% in the USA and 15% in the EU (in comparison to 2005 levels) – investments in battery technologies within the USA, the EU and Japan are set for 2005 and 2010 with an increase in investments for 2015 and 2020 (this increase replicates the increase between 2005 and 2010) – the USA and the EU achieve their 2020 renewable targets through the use of biofuels – total effort is consistent with Copenhagen Pledges and constraining temperature in 2100 to a 4.1ºC increase above pre-industrial levels.
535 ppm Policy	Fully flexible carbon permit trading occurs from 2015 onwards – investments in battery technologies within the USA, the EU and Japan are set for 2005 and 2010 (with no lower bound after this) – the USA and the EU achieve their 2020 renewable targets through the use of biofuels – total abatement effort is consistent with constraining temperature in 2100 to a 2.5ºC increase above pre-industrial levels.
450 ppm Policy	Fully flexible carbon permit trading occurs from 2015 onwards – investments in battery technologies within the USA, the EU and Japan are set for 2005 and 2010 (with no lower bound after this) – the USA and the EU achieve their 2020 renewable targets through the use of biofuels – total abatement effort is consistent with constraining temperature in 2100 to a 2ºC increase above pre-industrial levels.

Without direct incentives (via a carbon price or policy initiatives), investments in battery technologies within scenario 1 to 3 tend to fall to zero after 2010, with scenario 4 showing investments by the USA dipping between 2015 and 2025 and then ramping up in 2020 till a peak in 2050. The increased mobility in scenario 4 results in the case where traditional hybrids make up 30% of the USA vehicle fleet in 2040, PHEVs being 36% of the fleet in 2045, with EDVs emerging in 2060 to become the dominate vehicle type until 2100. Strong investments in battery technologies by China between 2025 and 2045 effectively shorten the spillover period between the OECD and China. This leads to the case where no traditional hybrids enter within China, but on the back of developments in the USA there is an emergence of PHEVs within China in 2040 (38% of the fleet) and EDVs in 2055 (35% of the fleet). As reflected in Figure 5, decreased mobility results in a situation where there is no incentive to invest in electric vehicles and biofuels solely supplement fossil fuels in all of the decreasing mobility scenarios. It should be noted that upon reviewing the timing of vehicle emergence that the results should be interpreted as representing the dominant market choices. With the choice of vehicles being modelled on cost, fringe vehicles that may be present in the fleet (but remain a small proportion of the market) are not included as there are no representations of stratified income or alternative preferences within the model. The introduction of continued investments in battery technologies in 2015 and 2020 within the Moderate Policy scenario aims to review the case where the electrification of the vehicle sector is driven by either policymakers or investors within the USA, the EU and Japan.

Figure 4. Vehicle Distribution – Limited Policy – Constant VKM compared to Increasing VKM

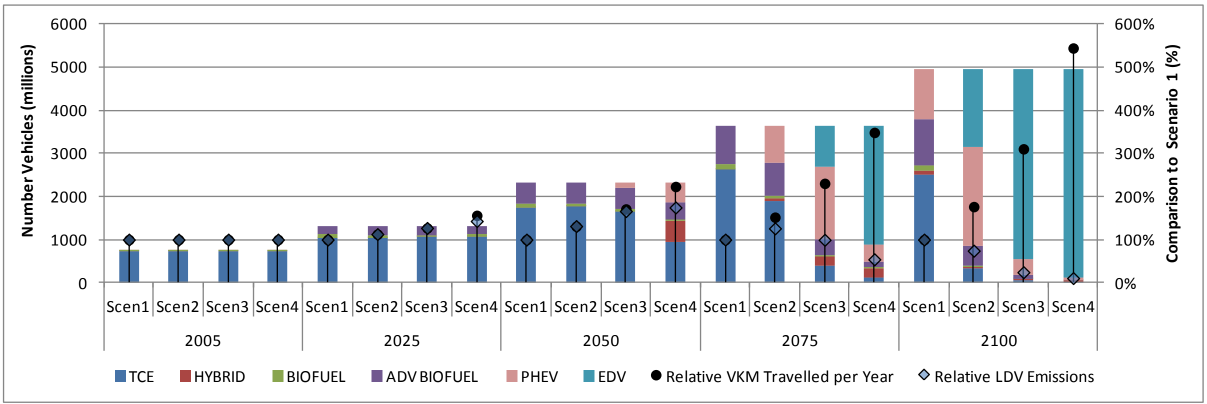
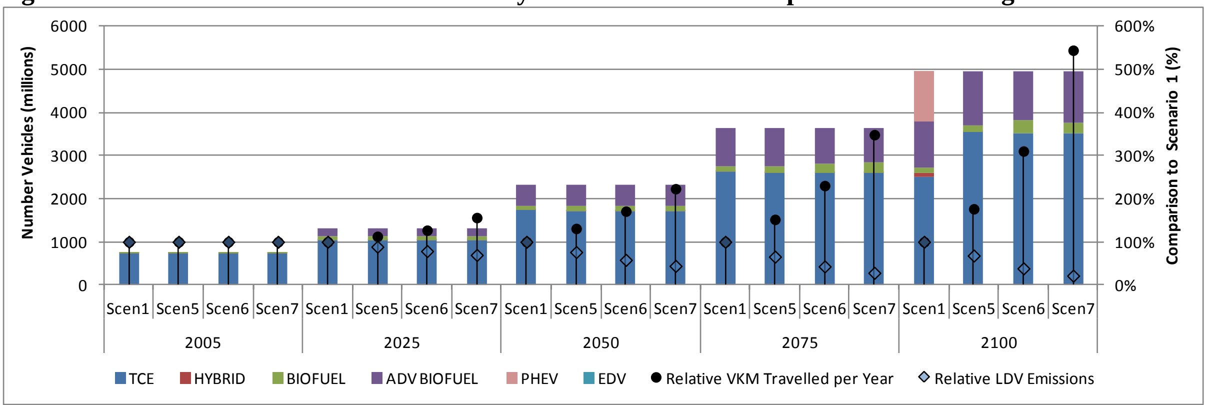


Figure 5. Vehicle Distribution – Limited Policy – Constant VKM compared to Decreasing VKM



Moderate Policy

A moderate policy scenario has been applied to review a scenario where some effort is made to reduce emissions within the USA and the EU. In addition to emission reduction targets for 2020, continued investments in battery related technologies are imposed from 2010 to 2020. These continued investments are intended to reflect a case where the electrification of the light duty vehicle sector is driven by either policymakers or even private investors. Set equal to the 'Energy Storage' totals within the public RD&D Budgets accessed through the IEA Energy Technologies RD 2011 edition database, the level of investments are highest in Japan, followed by the USA and then the EU. Investments within Japan are set at approximately 60 million 2005 USD in 2005 and 110 million in 2010. For the USA, investments are 52 million 2005 USD in 2005 and 87 million in 2010. Within the EU, 48 million in 2005 and 78 million in 2010 are the initial investment values. Putting these numbers in perspective, the IEA total investments for RD&D in 2010 (as reported in the IEA Energy Technologies RD 2011 database) were 10,968 million 2005 USD. Within the moderate policy scenario, projections for investments in 2015 and 2020 match the growth rate between 2005 and 2010. Investments in Japan increase to just over 200 million 2005 USD in 2015 and 370 million in 2020. For the USA 2015 investments are 146 million 2005 USD and 245 million in 2020. The EU increases investments in 2015 to 128 million 2005 USD and 210 million in 2020.

Figure 6 and Figure 7 review the global vehicle distribution that prevails under this scenario across the different trends in mobility that were noted in section 2, Table 1. With moderate carbon abatement policy applied and continuing investments in battery technologies after 2010, the electrification of light duty vehicles tends to occur before 2050 in all scenarios where mobility increases. Within scenario one, traditional hybrid vehicles become the dominant vehicle of choice within the USA in 2025, while the rest of the world tends to rely on a mixture of vehicles. Plug-in electric drive vehicles emerge as the dominate vehicle within the USA in 2045, while the rest of the world does not invest in electrification. Additional mobility tends to promote electrification with scenario two showing the adoption of PHEVs in the USA as early as 2035 and a trend towards electrification occurring within the rest of the world. During 2080, PHEVs are the dominant vehicle at the global level and the USA introduces EDVs in 2085. Scenario three matches the growth in VKM travelled within the USA (1.2% per annum) between 1985 and 2005 as noted within US EPA (2010). (US EPA, NHTSA, and the Californian Air Resources Board (2010: E-8) Labelled within Table 1 as moderate increase, it is a scenario that is likely in the future if wide spread investments in public transportation do not occur[11].

[11] This assumption is consistent with the low scenario developed within OCED and ITF (2012) which claims that a scenario with high public transport is associated with large investments and strong urbanisation effects. Such a scenario implies that "keeping mobility growth near it requires a strong and enduring policy commitment" (OECD and ITF (2012): 6).

Within this scenario electrification occurs more strongly across the globe, with similar trends in the introduction of vehicles within the USA prevailing – except for the earlier introduction of EDVs within 2065. The light duty vehicle transport sector of all regions tends to electrified by 2080, with some regions persisting with PHEVs for longer due to cost. Within the strongest mobility scenario, scenario four, traditional hybrids become the dominant vehicle by 2030 within the USA, with PHEVs then dominating in 2035 and EDVs coming in by 2060. In all of these scenarios, the USA drives the investments in R&D, with some investment occurring in China within the latter half of the century. Within all of the decreased mobility scenarios, there are no investments in battery related R&D after 2020 and scenarios four, five and six show the introduction of traditional hybrids during the middle of the century. With no continuation of investments in battery related R&D, these scenarios coincide with continued investments in the conversion of biofuel from woody biomass and a return to traditional combustion engine vehicles using a biofuel mixture after 2050, as shown in Figure 7. The initial level of investment for 2015 and 2010 within the moderate policy scenario are insufficient to introduce sustained electrification when mobility decreases.

Figure 6. Vehicle Distribution – Mod. Policy – Constant VKM compared to Increasing VKM

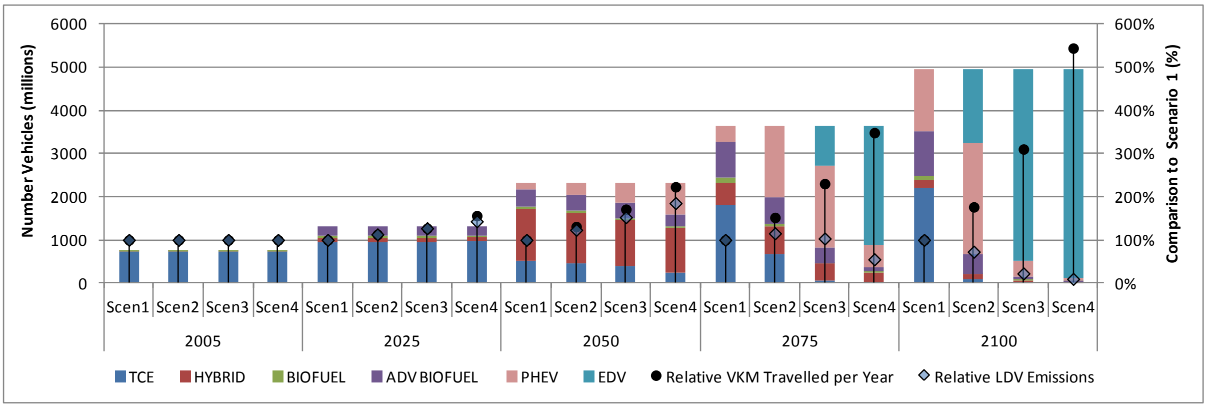


Figure 7. Vehicle Distribution – Mod. Policy – Constant VKM compared to Decreasing VKM

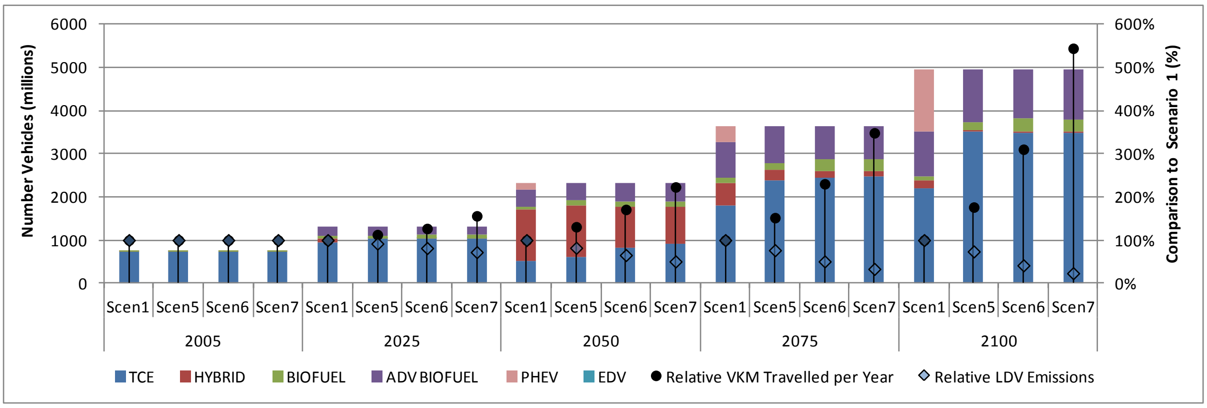
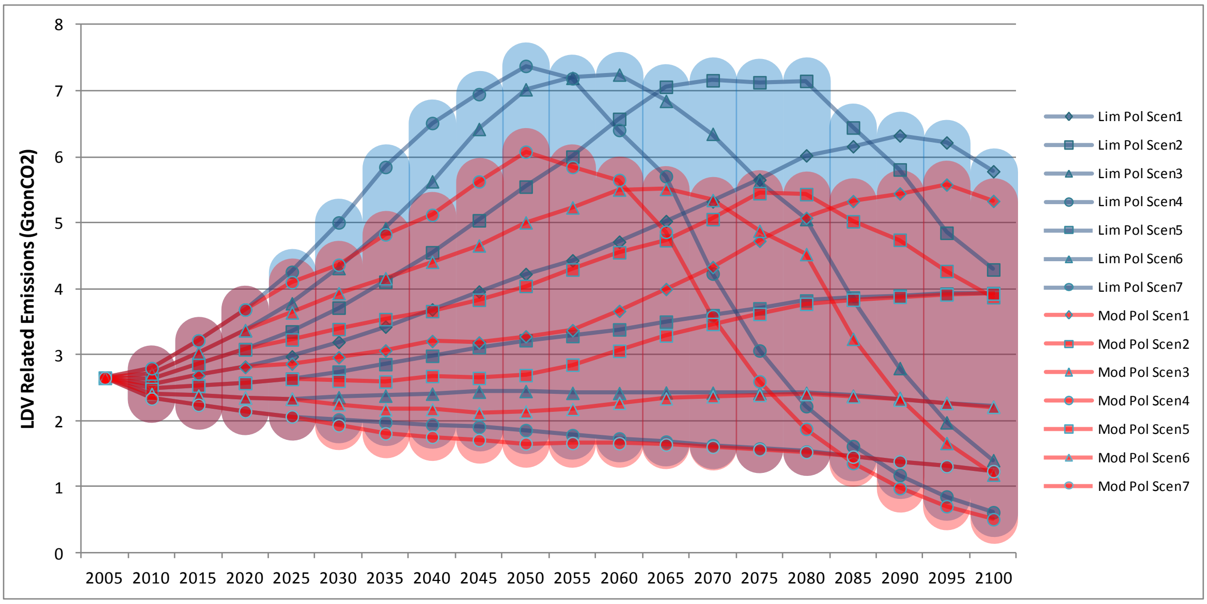


Figure 8 reviews the change in emissions attributed to the light duty vehicle sector and makes a comparison of the trends between the limited policy case and the moderate policy scenarios. With increased electrification, scenarios two, three and four with moderate policy applied show declines in emissions compared to the equivalent limited policy scenarios. Where a decrease in mobility has occurred, there is a temporary lull in emissions between 2030 and the early part of the second half of the century, with the fuel mixture returning to that within the limited policy state of the world. Within these decreased mobility scenarios, commercialisation of traditional hybrids occurs due to the investments specified between 2015 and 2020; however the prevailing price of oil and biofuels is not high enough to promote further investments aimed at introducing PHEVs or EDVs. The aggregate amount of emissions saved within the moderate policy scenarios (in comparison to the corresponding mobility scenario from the limited policy case) is the highest within scenario two, followed by scenario three and then four. Scenario two under the limited policy scenario resulted in 100 Gt of CO_2, compared to 80 Gt in the moderate policy scenario. The observation that the most conservative increased mobility scenario has the highest emissions savings reflects the prevailing trend towards electrification within scenarios with higher amounts of mobility and the effect of early investments in battery related technologies which caused the successful commercialisation of traditional hybrids within all scenarios.

Figure 8. LDV Emissions – Limited Policy Compared to Moderate Policy



535ppm Policy

The limited and moderate policy scenarios are representations of the world in situations that are consistent with its current state. The next two sets of scenarios assume that there are stringent climate policies in place which are aimed at stabilising world concentrations of GHGs. This first scenario aims at achieving a 550ppm CO2-eq concentration of GHGs by 2100 (consistent with the target of constraining temperature in 2100 to a 2.5ºC increase above pre-industrial levels) and is in place from 2015 onwards. The key objective is to study the role of the light duty vehicle transportation sector in achieving stabilisation policies and for this reason we remove constraints on policy participation and the timing of action. This policy scenario concentrates on the most efficient global policy and reviews how it would be affected by alternative mobility scenarios. The emission reduction targets for 2020 are removed and investments in battery related technologies for 2015 and 2020 are now unconstrained. By utilizing WITCH these scenarios simulate climate policy in an ideal environment in which all world regions agree on the stabilization target and credibly commit to achieve it. Regions receive emission allowances that can be traded in an international carbon market. All sectors, including transportation, are capped. Banking and borrowing is allowed within the solution and hence it reflects an inter-temporally optimal emissions reduction trajectory.

Figure 9 and Figure 10 review the optimal global vehicle distributions that achieve the 2.5ºC target at least cost. In all of the scenarios where mobility increases, some electrification occurs by 2045 to varying degrees across regions. Within scenario one, PHEVs enter first within China as they invest heavily in battery related technologies between 2035 and 2060, with the USA following and becoming the dominant investor in battery related technologies in 2060 – coinciding with the commercialisation of EDVs. Traditional hybrids remain a fringe vehicle in most regions, with notable shares only occurring within the EU (30% of the fleet in 2055) and India (33% of the fleet in 2050). Reflecting the scale and dominance of investments in battery related technologies, investments in the conversion of biofuels from biomass tend to be limited after 2035. Scenario two also has China investing heavily in battery related technologies, this time as early as 2020 and until 2045, with the USA becoming the dominant player between 2050 and 2060. PHEVs appear as the dominant vehicle within China and the USA in 2040, while EDVs enter in China in 2050 and within the USA in 2060. Traditional hybrids remain fringe vehicles in most regions, except for China (36% of the fleet in 2035), LACA (27% in 2050), and the EU – where they become a dominate vehicle type in 2045 (32% of the fleet in 2045), 2050 (55% of the fleet) and 2055 (36% of the fleet).

Scenario three shows similar investment trends in battery related technologies, except that a greater range of regions start to invest between 2030 and 2045. In 2030, China invests at level that is 48% of the global share; the USA invests at level that corresponds with 32%, while MENA, TE, India and LACA account for the rest of the investment. By 2040, the USA invests at the peak of their contributions to global investments with 46% of global investments, with China declining to 10% and

MENA (13%), TE (13%), India (11%) and LACA (5%) account for the rest of investments. The commercialisation of vehicles reflect these investment trends, with China and the USA utilising PHEVs by 2035 and EDVs entering in China in 2045, 2050 for the USA, TE, MENA and India. With carbon policy commitments across all periods and increased mobility, scenario three also has traditional hybrids acting as an interim technology, entering in a wider range of regions between 2030 and 2045. Scenario four leads to the situation where the USA leads the global investments in battery related technologies for a long period (with China only gaining a higher global share in 2030). In 2035, the USA invests at a level which corresponds with 52% of global investment, rises to 92% in 2050 and remains at a similar USD level until declining after 2085. Reflecting these investments, traditional hybrids become the dominant vehicle within the USA in 2025, with PHEVs quickly replacing them in 2030 and EDVs dominating the fleet globally by 2050. The increase in energy demand associated with the increased mobility scenarios is shown in Figure 11.

Figure 9. Vehicle Distribution – 535ppm Policy – Constant VKM compared to Increasing VKM

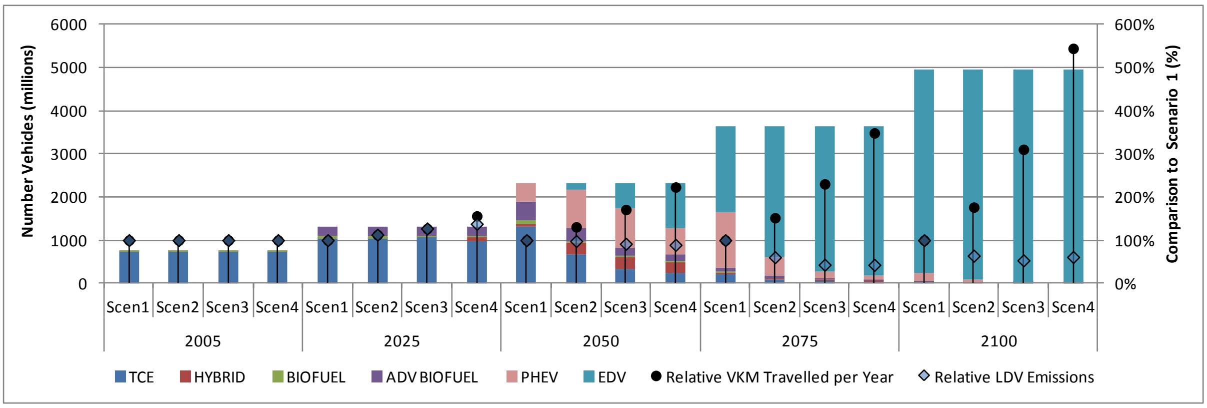


Figure 10. Vehicle Distribution – 535ppm Policy – Constant VKM compared to Decreasing VKM

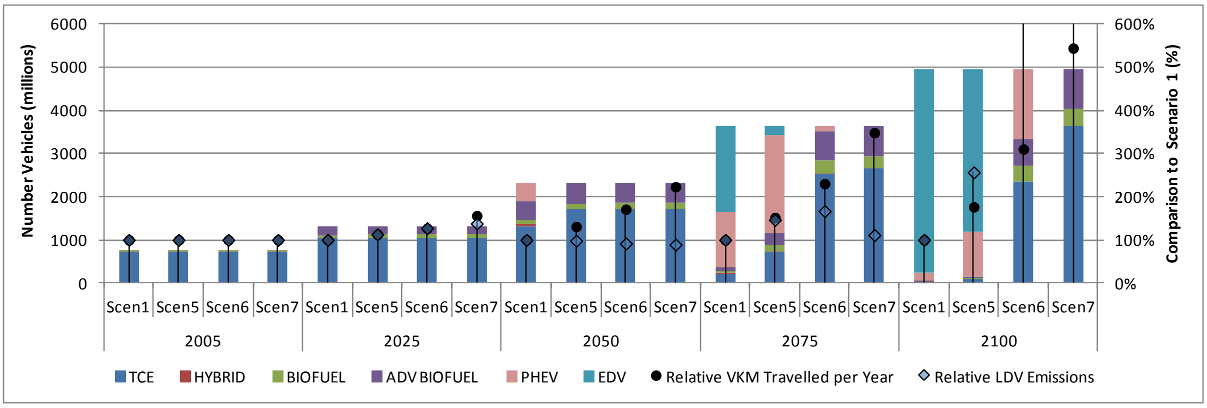


Figure 10 reviews the impact that decreased mobility has on climate abatement as the electrification of the light duty vehicle transportation sector is notably delayed in the two most extreme decreased mobility scenarios. With relative LDV emissions in Figure 10 tracking the difference in the level of emissions in comparison to scenario one, the lack of vehicle change results in a case where the relative emissions explode dramatically with no (or relatively little) investment in battery related technologies. As a result, policy costs as a percentage of discounted GDP are highest in scenario seven. Aggregate light duty vehicle emission levels remain high in these two scenarios and are approximately 98% for scenario six and 100% for scenario seven (in comparison to their counterparts under the limited policy scenario). With similar levels of emissions from LDV transport, less aggregate fuel use and the changes in the energy sector are sufficient to reach the emission reductions needed. The reduction in energy demand associated with the decreased mobility scenarios is reflected in Figure 12. These small differences in aggregate emissions within the decreased mobility scenarios are quite distinct when you compare them to the difference in aggregate emissions (in comparison to their counterparts under the limited policy scenario) for the increasing mobility scenarios; these being 53% for scenario one, 45% for scenario two, 48% for scenario three, 56% for scenario four and 72% in scenario five.

Figure 11. Primary Energy Supply – 535ppm Policy – Overall Economy and LDV Fuel Use – Inc. VKM

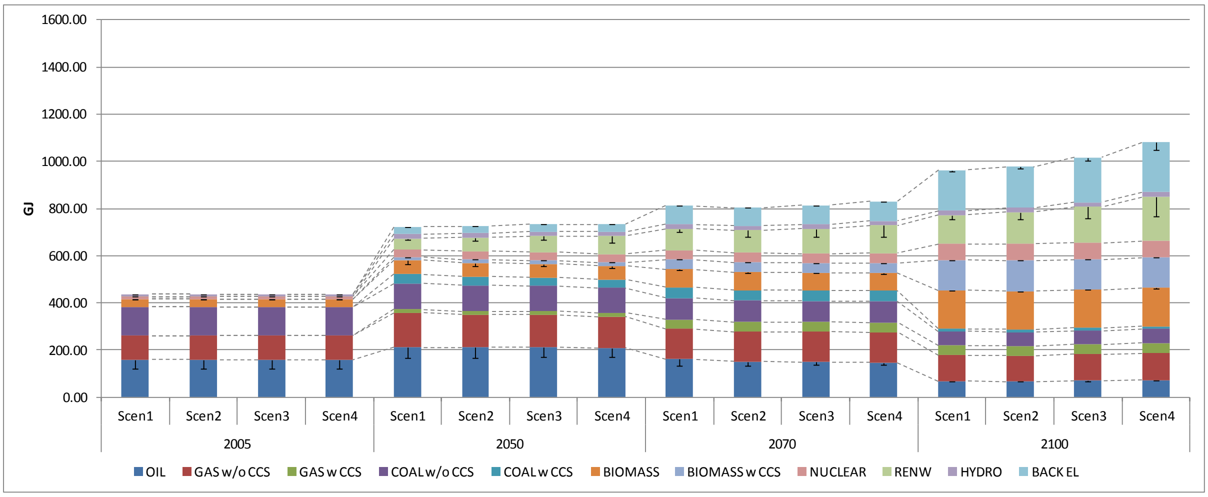
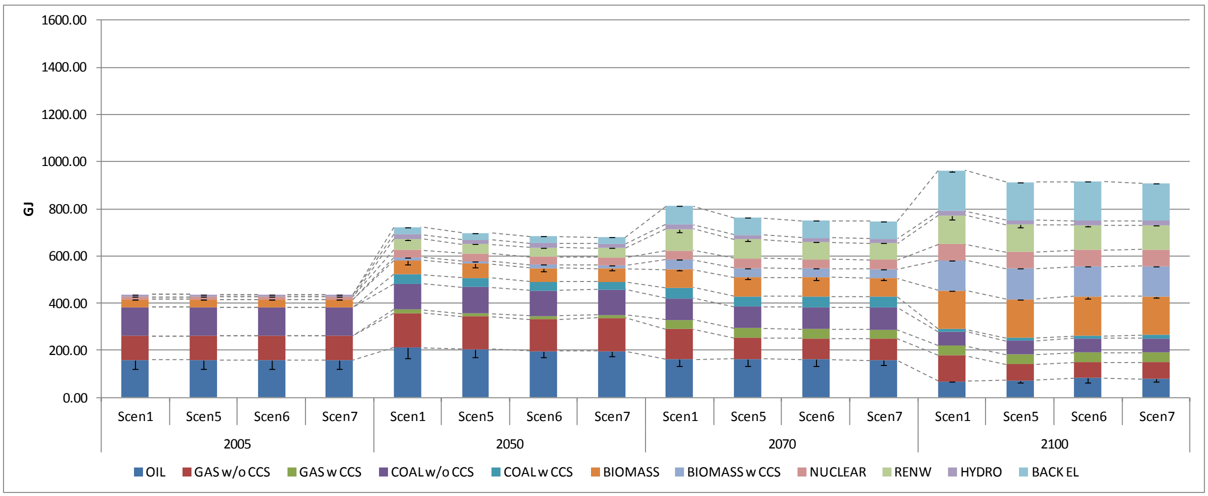


Figure 12. Primary Energy Supply – 535ppm Policy – Overall Economy and LDV Fuel Use – Dec. VKM



While the importance of electrification in achieving a 550ppm CO2-eq concentration of GHGs by 2100 was established in Bosetti and Longden (2012), these results show a direct relationship between increased mobility and the need to invest in battery related technologies. As mobility increases investments also increase and occur more widely across regions. In some cases where there are conservative increases in mobility, traditional hybrids do not enter to decrease emissions in early periods as there is no urgency to abate.

450ppm Policy

This scenario aims at replicating an effort which achieves significant carbon reductions and achieves a 450ppm CO2-eq concentration of GHGs by 2100 (consistent with the target of constraining temperature in 2100 to a 2ºC increase above pre-industrial levels). Regions receive emission allowances that can be traded in an international carbon market and this market is in place from 2015 onwards. This scenario concentrates on the most efficient policy and reviews how it would be affected by alternative mobility scenarios. The emission reduction targets for 2020 are again removed and investments in battery related technologies for 2015 and 2020 remain unconstrained. Figure 13 and Figure 14 review the vehicle distributions at a global level. Reflecting a higher level of emissions abatement, the electrification of the light duty vehicle transport sector occurs across all scenarios with PHEVs appearing as the dominant vehicle type within the increased mobility scenarios as early as 2020 or 2025 in scenarios two, three and four. Within all scenarios (except for scenario six and seven) the need to make reductions in emissions causes the USA to continue investments in battery related technologies in 2015 and 2020, without the lull in investments seen in most of the less stringent climate target scenarios. In comparison to the 2010 level of battery related investment sourced from the RD&D Budgets within the IEA Energy Technologies RD 2011 edition database, scenario one has a 2015 level of investment that is 9% higher than that from the IEA data, scenario two has investments in 2015 that are almost four times higher while scenarios three and four lead to even more dramatic increases in investments that are aimed at introducing PHEVs as the dominant vehicle within the USA and a commercially viable technology by 2020.

Figure 13. Vehicle Distribution – 450ppm Policy – Constant VKM compared to Increasing VKM

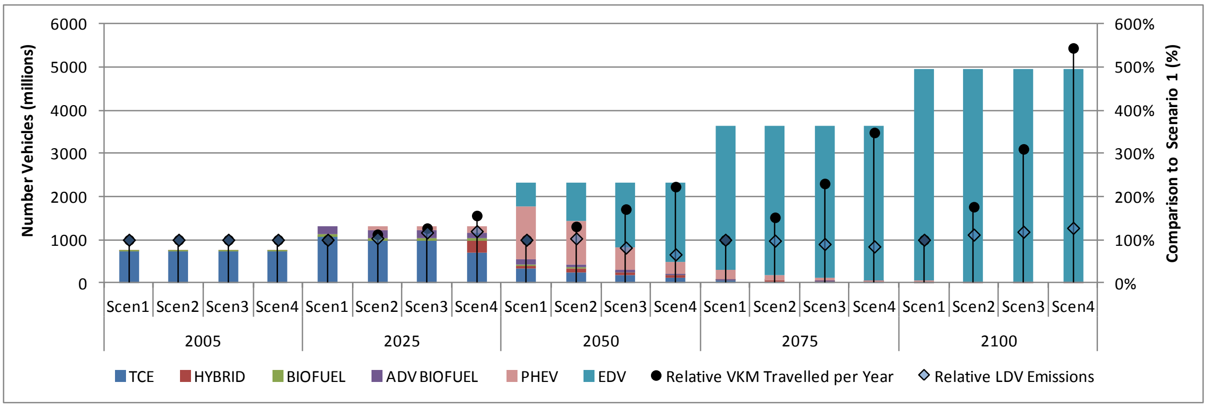
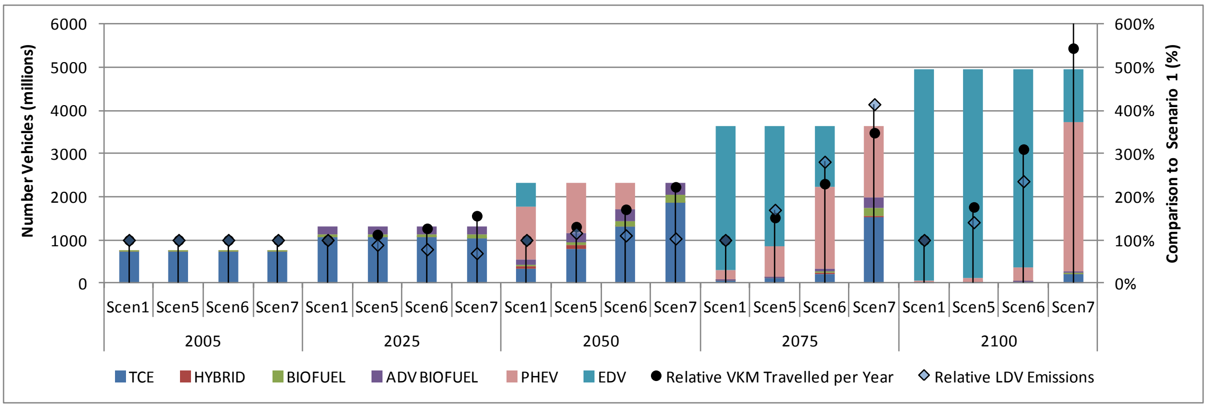
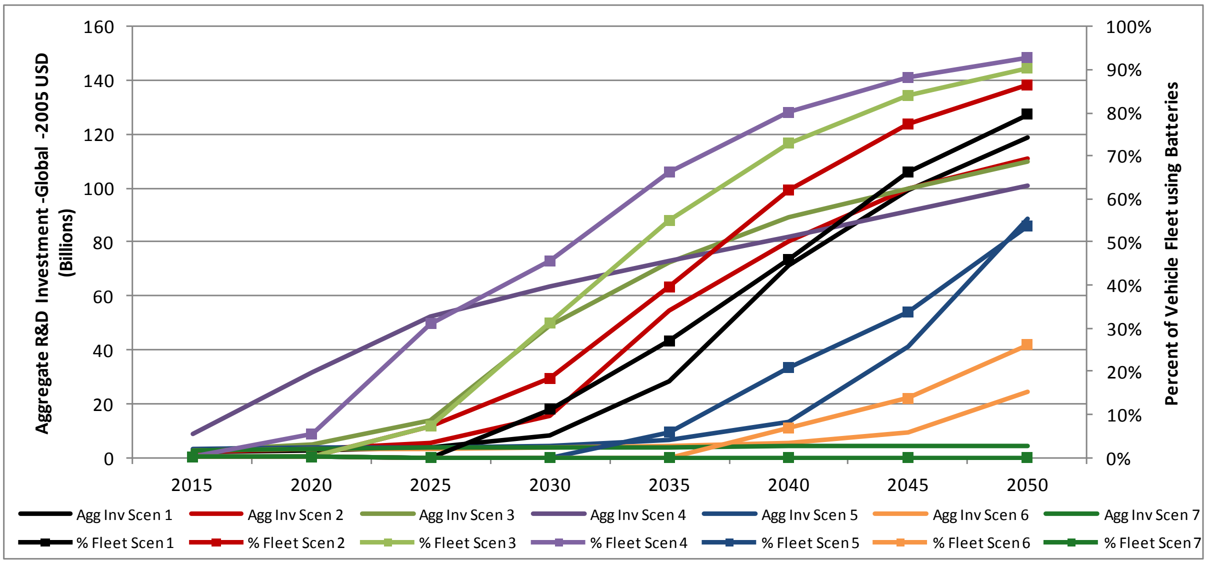


Figure 14. Vehicle Distribution – 450ppm Policy – Constant VKM compared to Increasing VKM



The focus of achieving a 450ppm target and constraining temperature in 2100 to a 2ºC increase above pre-industrial levels implies large investments in battery related technologies from 2015 and less investments in technologies related to the conversion of biofuel from biomass. Figure 15 reviews the aggregate amount of investments in battery related R&D and the share of the LDV fleet that is implied. While stable travel trends may quell the urgency for investments until 2020 (as in scenario one), even the most conservatively amplified travel scenario (scenario two) shows no lull in investments in 2015 as there are increasing investments within battery related technologies in the USA from 2015 until 2035. This leads to a situation in all scenarios where PHEVs become the dominant vehicle type in the USA by 2025 and the introduction of EDVs within the USA fleet occurs by 2045. The highest mobility scenario reviewed (scenario four) shows a need for PHEVs to become the dominant vehicle type in the USA by 2020 and the introduction of EDVs within the USA fleet occurs by 2030. Note that this is a drastic change within the vehicle fleet in a relative small period of time as this model assumes that alternative vehicle types only enter when they are near perfect substitutes in cost as well as other attributes that may impact consumer preferences such as speed, power, range and refuelling demands. This is reflected within Figure 15 where upon reviewing the trends for scenario 4 one can see large investments (over 8.5 billion USD in 2015) occurring without immediate increases in battery related vehicles. The urgency of emissions abatement leads to the case where no traditional hybrids are introduced within the USA and instead there are investments to immediately commercialise PHEVs. Traditional hybrids tend to be invested in most heavily in 2020 and in a limited amount of regions as there is a quick transition to PHEVs. Otherwise, Figure 15 shows the stable pattern of increased electrification with increases in mobility – as reflected in the curves with dashes and squares. The pattern in aggregate investments changes over the scenarios and this can be seen across the two highest mobility scenarios where there are gains from early investments in the technology. These gains are sourced from the 'standing on the shoulders of giants' effect and are highest in the 2015-2050 period due to the urgency of abatement that occurs with increased mobility.

Figure 15. Aggregate R&D Investments and the Composition of the LDV Fleet



The ability of reaching a 450ppm target does not rely on the light duty transport sector alone and within these scenarios there is a decarbonisation of other sectors as well, including freight transport and the energy supply. Figure 16 and Figure 17 show the changes to the energy supply within the economy and the share attributed to LDVs. Within scenarios one to four there is a gradual move away from fossil fuels to low carbon options with renewable sources dominating the fuel mixture when electrification occurs. Scenarios five to seven are associated with decreased energy demand and less need to develop an electric backstop technology (such as advanced solar). Within scenario one, global oil use in the LDV transport sector peaks in 2015, while in scenario four, the effect of increased travel is only partially offset by electrification in some regions until oil use peaks at a global level in 2025.

Figure 16. Primary Energy Supply – 450ppm Policy – Overall Economy and LDV Fuel Use – Inc. VKM

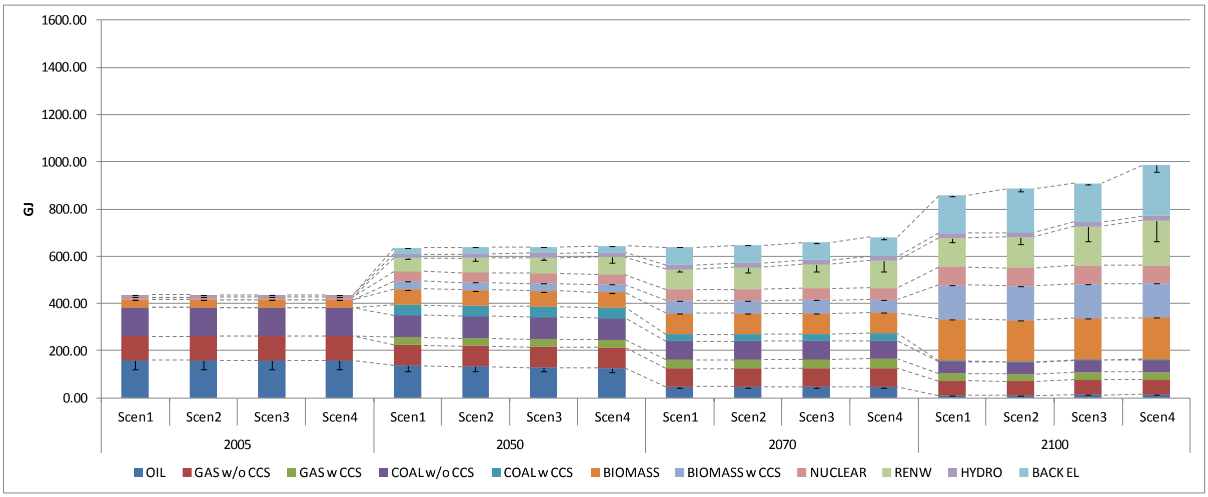
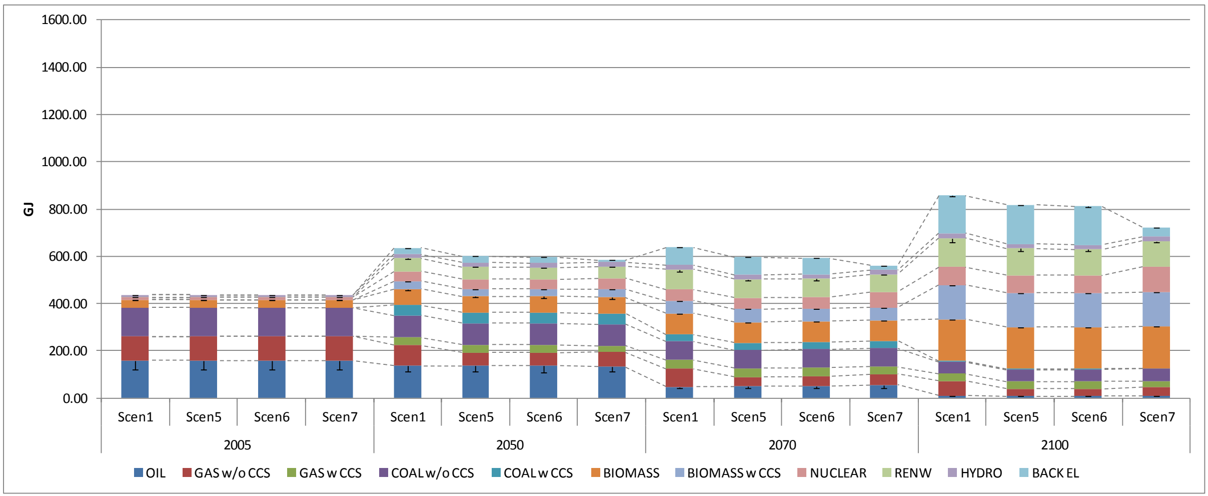


Figure 17. Primary Energy Supply – 450ppm Policy – Overall Economy and LDV Fuel Use – Dec. VKM



Section 5 – Conclusion

Focusing on light duty vehicle travel per year, this paper reviews the impact of changes in the amount of kilometres travelled on the profile of vehicle ownership subject to the cost of fuel and carbon costs. Simulation results show that changes in the kilometres driven per year using light duty vehicles have a notable effect on the optimal vehicle fleet composition. In addition to detailing various fleet profiles that have been determined using different travel trends and carbon policies, the model utilised in this paper provides the optimal level of investments in battery related research and research into the conversion of biomass into biofuels. The range of emissions from light duty vehicles for the scenarios that were covered in the paper are shown in Figure 18, while the vehicle distributions for the scenarios where VKM are either constant or increasing is shown in Figure 19. A focus on abatement efforts in relation to automobile electrification presents a summary of the key conclusions of the paper. Within scenarios with higher abatement policy and higher mobility, the electrification of the transport sector is most accute. Comparing the highest mobility scenario (scenario 4) to a constant mobility scenario (scenario 1) shows the urgency of abatement that is needed with trends of kilometres travelled that are no inconsistent with historical data. Deviations in the global fleet of vehicles across carbon abatement targets occur in all scenarios, except for the extreme case (scenario seven) where mobility decreases at 1.2% per annum and the fleet remains the same as in the limited policy baseline. For the vehicle composition to be the same across carbon abatement scenarios, this extreme mobility decrease would have to occur worldwide and in all regions. As noted, a scenario where notable decreases in mobility occurs is unlikely in the future unless there are wide spread investments in public transportation within all regions.

Figure 18. Emissions – Limited Policy Compared to 535ppm and 450ppm Policy Scenarios

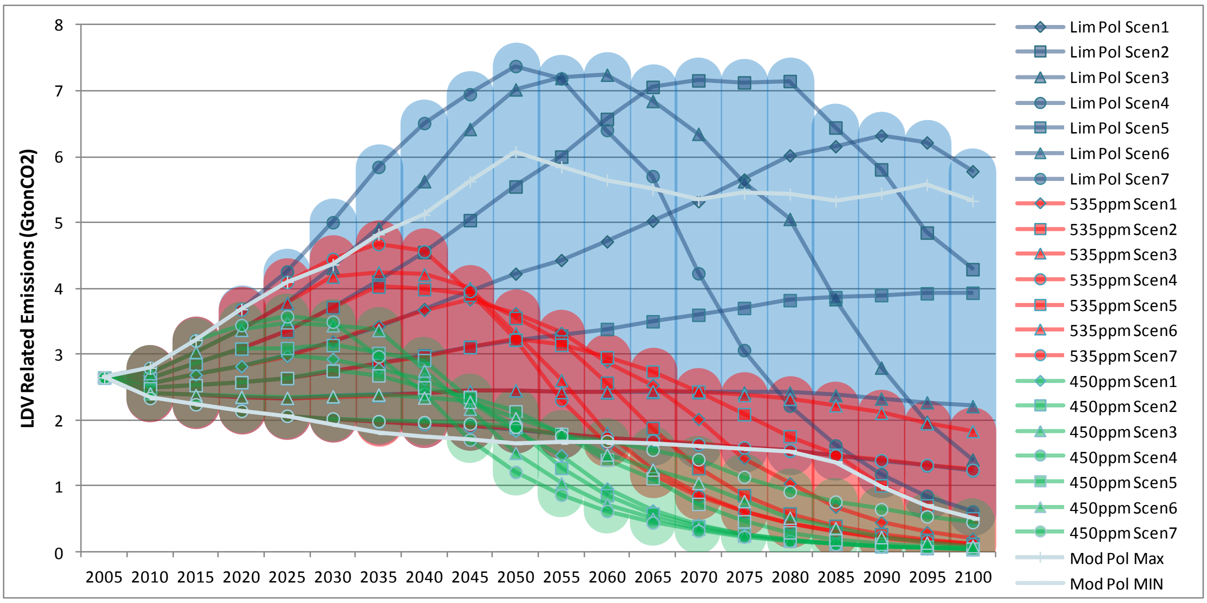
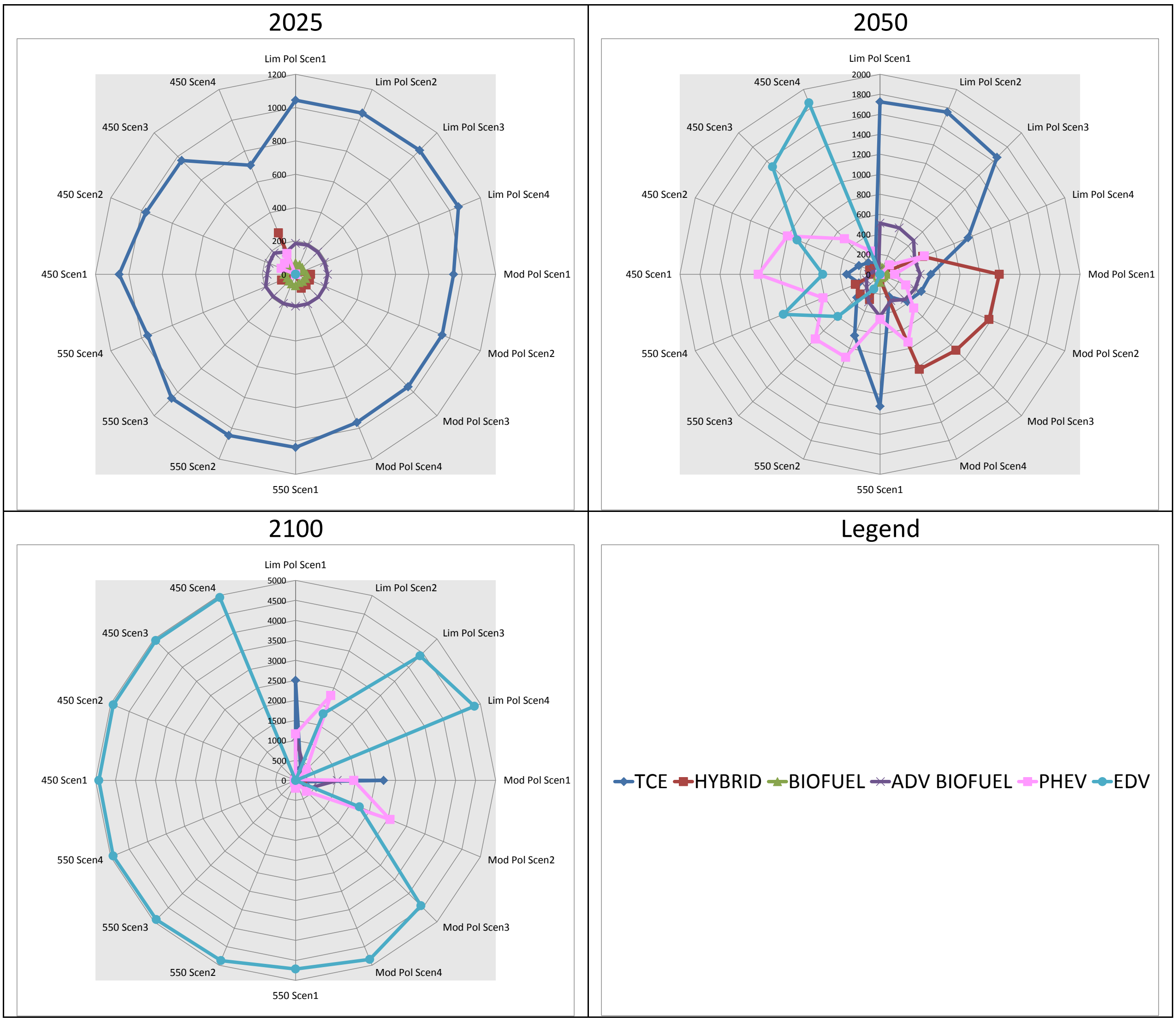


Figure 19. Vehicle Distributions – All Scenarios



Note: the radar plots start from the least stringent case (Limited Policy with constant VKM) and moving in a clock-wise direction tends to coincide with the scenarios becoming more stringent and having more electrification. The scale plots the global amount of vehicles in millions.

To set a baseline for the analysis a limited policy baseline is established based on current trends without the effect of prescribed carbon abatement policies. Within the limited policy scenario, where no notable policy to abate carbon emissions occurs, there are widespread differences in vehicle compostion depending upon the amount of mobility that occurs. In the case where carbon abatement and stable/increased mobility do occur, there is a trend towards alternative vehicles even in a case where moderate policy takes place. However, with no continuation of investments in battery related R&D after the initial 2020 emissions target is met, moderate policy scenarios coincide with continued investments in the conversion of biofuel from woody biomass and a return to traditional combustion engine vehicles using a biofuel mixture after 2050. A global effort to contain temperature increases in

2100 to 2.5ºC above pre-industrial levels results in a situation where increased mobility leads to the electrification of LDVs by 2045. In comparison to less stringent policies, the achievement of a 550ppm GHG concentration in 2100 implies higher investments in battery related technologies and a wider effort across regions. The impact that decreased mobility has on climate abatement is to notably delay the electrification of the light duty vehicle transportation sector in the two most extreme decreased mobility scenarios.

The focus of achieving a 450ppm target and constraining temperature in 2100 to a 2ºC increase above pre-industrial levels implies large investments in battery related technologies from 2015 and less investments in technologies related to the conversion of biofuel from biomass. While stable travel trends may quell the urgency for investments until 2020, even the most conservatively amplified mobility scenario shows increasing investments within battery related technologies in the USA from 2015 until 2035. The highest mobility scenario reviewed (which coincides with an increase in vehicle kilometres of 1.8% per annum) shows a need for PHEVs to become the dominant vehicle type in the USA by 2020 and the introduction of EDVs within the USA fleet occurs by 2030. As noted, this would consist of a drastic change within the vehicle fleet in a relative small period of time as this model assumes that alternative vehicle types only enter when they are near perfect substitutes in cost as well as other attributes that may impact consumer preferences such as speed, power, range and refuelling demands. This is reflected within Figure 15 where the case of an increase in vehicle kilometres of 1.8% per annum coincides with large investments (over 8.5 billion USD globally in 2015) occurring without immediate increases in the number of battery based vehicles. Achieving a 450ppm GHG concentration target is viable with conserative electrification of transport and decreased mobility that coincides with decreased energy demand and less need to develop an electric backstop technology (such as advanced solar). However, it should be noted that a scenario where notable decreases in mobility occurs is unlikely to occur in the future unless there are wide spread investments in public transportation within all regions.

This paper has applied mobility increases at the same rate across the OECD and non-OECD regions and future work is aimed at investigating the impact of differences in patterns across regions. This paper also reviews light duty vehicles alone and future work will focus on the incorporation of switching between transport options. The development of mobility scenarios appropriate for the non-OECD is also a key priority of forthcoming work and related to the question of transport alternatives as well as the feasibility of decreased mobility at the global scale. As noted in the prevailing trends covered in section 2, there is persistent demand for mobility using light duty vehicles and this is sure to continue in the future without a radical shift in preferences or mobility options.

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Appendix

Table 1A Variables related to Equations in Section 2

Variable	Description
W	Welfare
U	Instantaneous utility
CG	Gross consumption
C	Consumption
R	Discount factor
Y	Net output
I_c	Investment in final good
$I_{R\&D,j}$	Investment in energy R&D
I_j	Investment in technology j
$O\&M_j$	Investment in operation and maintenance
I_{road}	Investment in road vehicles
$O\&M_{road}$	Operation and maintenance costs for road vehicles
$FE_{road,j}$	Fuel Expenditure for road vehicles and technology j
K_{road}	Stock of road vehicle capital
D	Depreciation rate of road vehicle capital stock
SC_{road}	Investment cost of road vehicles
RK_{TECH}	Research Capital in certain technology
D_K	Rate of depreciation (for capital not an LDV)
RI_{TECH}	Research Investments
P_{EDV}	Price of EDV
$RSpill$	Research Spillover after certain patent period
EF_{ADVB}	Efficiency of Adv Biofuel Conversion

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