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Light Duty Vehicle Transportation and Global Climate Policy: The Importance of Electric Drive Vehicles

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

JEL Classification: Q54, R41, O3

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Abstract

With a focus on establishing whether climate targets can be met under different personal transport scenarios we introduce a transport sector representing the use and profile of light domestic vehicles (LDVs) into the integrated assessment model WITCH. In doing so we develop long term projections of light domestic vehicle use and define potential synergies between innovation in the transportation sector and the energy sector. By modelling the demand for LDVs, the use of fuels, and the types of vehicles introduced we can analyse the potential impacts on the whole economy. We find that with large increases in the use of vehicles in many regions around the globe, the electrification of LDVs is important in achieving cost effective climate targets and minimising the impact of transportation on other sectors of the economy.

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Section 1 – Introduction

Mobility and the demand for personalised transport have been identified as having a strong association with national income and improved development (Dargay and Gately, 1999 and WBCSD, 2001). As national income increases, so too does the rate of automobile ownership and this has created an unsustainable relationship between rising income and emissions (Schipper and Fulton, 2003). During the 1990 to 2005 period which corresponds to the Kyoto Protocol's benchmark year and the year the Protocol entered into force, the global emissions attributed to road transport rose from 624.2 $kgCO_2$ per capita to 714.5 $kgCO_2$ per capita, a slightly higher rate than total per capita emissions. Underlying this increase was a 19% increase in per capita emissions from within the OECD and a 25% increase in per capita emissions by non-OECD nations (based on their respective 1990 per capita level)[1]. With a continuation of the coupling of income growth and emissions being forecasted (WBCSD, 2001), successful climate policy to stabilise greenhouse gases will need to account for the lack of clear carbon free alternatives in the transport sector. An increasingly important consideration, especially in fast growing countries, the profile of transport will have repercussions on the global energy market, as well as on local and global pollutants. With increased demand for transport from non-OECD countries, the composition of the Light Duty Vehicle (LDV) transport sector becomes an important determinant of the success of climate policy. The 4th IPCC Assessment report, working group III, notes that CO_2 emissions are proportional to energy use and that virtually all of transport energy is derived from oil-based fuels – with diesel making up 31% and petrol 47% of total energy in 2004. (Kahn Ribeiro et al., 2007: 328) With forecasts of transport demand in the non-OECD growing at approximately three times the rate of those of the OECD (Kahn Ribeiro et al., 2007: 333), the global modelling of transport demand and the energy market proves to be an important exercise.

In order to analyse long term trends in transport and their repercussions on the rest of the economy we introduce a transport module representing the use and profile of light duty vehicles (LDVs) into the integrated assessment model WITCH (Bosetti *et al*, 2006; Bosetti, Massetti and Tavoni, 2007; Bosetti *et al*, 2009). The modification to the WITCH model has been designed to incorporate a range of competing vehicle types[2] to assist in the determination of the dominant modes of LDV transport that

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[1] Data sourced from IEA (2010) – CO_2 Emissions from Fuel Combustion Statistics – accessed on 7 July 2011.

[2] The range of vehicles introduced in WITCH 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. These include traditional combustion petrol fuelled vehicles (TCARS), diesel fuelled vehicles (DIESEL), traditional petrol fuelled hybrid vehicles (TR_HYBRID), diesel fuelled hybrid vehicles (D_HYBRID), first generation/traditional biofuels fuelled vehicles (TR_BIOFUEL), biodiesel fuelled vehicles (BIODIESEL), and natural gas fuelled vehicles (LPG). In addition to these vehicles that existed in some shape or form in 2005, we have also incorporated plug-in hybrid vehicles (INT_PHEV) and electric drive vehicles (INT_EDV) to represent

will tend to be selected to adequately satisfy demand for mobility. Personal light duty vehicles have been selected as the vehicle type of interest as they have been identified as being one of the most favoured modes of transport and also one of the most damaging (Chapman, 2007). The addition of the transport module into the integrated assessment model allows us to evaluate how the choice between LDVs will affect emissions as well as how these choices are likely to be impacted by climate change policies. The incorporation of the LDV transport sector within the WITCH model has been conducted in a manner which allows for a range of emission mitigations to be possible, this includes: increased fuel efficiency, the introduction of alternative fuels and vehicle types, as well as curbed demand through decreases in the amount of kilometres travelled using LDVs per year.

In addition to describing the LDV transport sector model, the objective of the present paper is threefold. First, we review the long term projections for light duty vehicles at a global and regional level. By incorporating LDV transport as a new module in an integrated assessment model we are able to investigate the long term macroeconomic and environmental impacts of transportation for different parts of the globe. Second, we look at the role played by the transportation sector when climate change policy is in place with specific attention to the role played by alternative technological and behavioural assumptions. The mutual interactions of the LDV transport sector with the demand for energy by the rest of the non-electric sectors, as well as investments in the power sector, the incentives to develop a carbon-free substitute for oil in transport and an international carbon market are all taken into account. Thirdly, we investigate a range of transportation specific scenarios to test the model and review how they impact global emissions and policy costs.

Climate change policies aiming to stabilise Greenhouse Gas concentrations in the atmosphere at low levels are expected to need a corresponding contraction in the level of fossil fuel use. An exception would be the adoption of CO2 capturing technologies, which are not applicable to mobile vehicles. This, and the lack of readily available alternative transportation modes make the transport sector heavily dependent upon oil. 54.5% of the OECD's total final consumption of oil was devoted to transport in 2008 – 84% of which was consumed by road transport[3]. Additionally, motor gasoline use in the transport sector within the United States accounts for approximately 47% of the carbon emissions from the use of petroleum and 19% of total US carbon dioxide emissions[4]. The subsequent analysis will show that the cost of climate policy is notably higher when continued reliance on fossil fuels in the transport sector occurs, as other sectors have to compensate for this rigidity. This is true

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the types of vehicles being introduced onto the market in the years around 2010 – such as the Chevrolet Volt and the Nissan LEAF. Vehicles fuelled with advanced biofuel also exist within the model.

[3] Data sourced from IEA (2010) on 19 January 2011.

[4] Data sourced from US EIA (2008) on 19 January 2011.

even with the allowance for strong improvements in fuel efficiency, improved advanced biofuel conversion processes, and the wide spread use of currently available hybrid vehicles.

The paper is made up of the following sections. Section 2 provides an overview of the WITCH model and the structure of the transportation module. Within section 3 we discuss the no policy long term projection for the transport sector and its implications on oil dynamics and emissions. Section 4 reviews a climate stabilization scenario with specific attention to behavioural and technological assumptions for the transport sector. As part of a sensitivity analysis, this section also reviews cases where climate stabilisation occurs with specific constraints on the model. The concluding section is used to draw an overall assessment of the findings presented in the paper.

Section 2 – Modelling long term LDVs projections

Although long term scenarios and forecasts for the global transportation sector have become more common, the range of studies is still not expansive. This is coupled with a lack of comprehensive national data across all major countries/regions and an orientation of much of the literature towards the regional, urban or national level. Amongst the research with an international focus is the study by Dargay and Gately (1999) which established a relationship between national income and vehicle ownership for a range of countries and applied the resulting model to the task of setting projections from 1992 to 2015. The projections are based on short-run and long-run income elasticities for vehicle ownership estimated using a Gompertz function to approximate the implied vehicle/population ratio. In closing the paper, Dargay and Gately (1999) acknowledge that a more complex model may assist in improving projections, but in light of unavailable data, the simple model using per capita income does provide substantial explanatory power. A potential rationale for this explanatory power may be offered by Schafer and Victor (2000) whom discuss mobility as being a function of both time and monetary budgets. They contend that constraints of time and money result in a consistent amount of travel across cultures and countries – a relationship which would assist in the estimation of aggregate and long-term transportation scenarios. Kahn Ribeiro et al. (2007) note that in addition to worldwide travel studies finding a constant time budget, a rise in income has led to a shift towards faster and more energy intensive modes of transport. In discussing this, the IPCC report ‘Climate Change 2007: Mitigation’ notes that automobile travel accounts for 15-30% of trips in developing countries, in comparison to 50% and 90% within Western Europe and the United States, respectively. (Kahn Ribeiro et al., 2007: 329) With the growth rate of economic development identified as a primary driver of transport demand, rapid growth in transport demand is expected over the next several decades within developing countries. In line with these expectations, Kahn Ribeiro et al. (2007) review the literature and find that considerable growth in travel occurs in even the most conservative economic scenarios. (Kahn Ribeiro et al., 2007: 332) As a prelude to our own results in section 3 and 4, the WITCH model forecasts that 2050 levels of vehicle ownership in the OECD will be 48% higher than 2005 levels. In the non-OECD, the 2050 level of ownership is eight times higher than the 2005 level. This leads to a situation where the non-OECD will have 89% more vehicles than the OCED in 2050. At the global level, the number of vehicles in 2050 is approximately three times the 2005 level. This global level is slightly higher than the corresponding reference case presented by the World Business Council for Sustainable Development in ‘Mobility 2030: Meeting the Challenges to Sustainability’ (WBCSD, 2004) and the levels reported for the International Energy Agency’s Mobility Model (IEA Mo Mo) within Fulton et al. (2009).

Table 1 summarises a range of models providing long term forecasts of transportation trends at a global and/or regional level. The version of the WITCH model introduced within this paper has been included in the table as part of a comparison to the other models. A key difference to many of the models is that the WITCH model assumes an exogenous demand for the level of mobility which is related to GDP and does not change with the amount and profile of energy being supplied within the model. This is an important feature as it tests the sensitivity of climate policy scenarios to a given demand for fuels from within the transport sector (subject to the costs of vehicles, the type and cost of fuel used and carbon pricing). Upon reviewing table 1, it can be noted that a range of models do look at long-term forecasts for the transport sector and that amongst the models reviewed there is disparity in the approach used, the time-line applied and whether the model is a global integrated assessment model. Further to this, table 1 identifies the distinguishing features of the WITCH model in that it is an integrated assessment model (IAM) which uses GDP as a key determinant in establishing the demand for road transport and mobility; while specifying technological changes and the specific vehicle types that emerge within the transport sector and the impact this has on the energy sector through the amount and type of fuel demanded. The approach undertaken to achieve this is the direct modelling of the changes in the cost of vehicles, operation and maintenance costs, carbon prices, and the cost of fuel, as the determinants of the introduction of different vehicle types. With a linear choice across technologies using a Leontief function of the costs involved, the model selects the range of vehicles which simultaneously meets household demand for mobility, maximises non-transport based consumption, and achieves the given climate target. In addition, the modelling of technical change in advanced biofuel conversion and battery technology (used in hybrids and electric drive vehicles) has been achieved with the implementation of learning by searching relationships which represent the effect of research and development investments in these technologies.

Table 1. Long Term Transportation Models

MODELS	IAM	SPECIFIES VEHICLE TYPES	Independent Individual Transport	Independent Freight / Purchased Transport	TYPE OF FUELS	USES GDP IN ESTIMATING ROAD TRANSPORT	GLOBAL / REGIONAL FOCUS	FORECAST TIMELINE	REFERENCE
APEIS-IEA (AIM)	✔	✔	✔	✔	Oil, Gas. Biofuel, Hydrogen, Electricity	✕	Regional - Asis Pacific	2000 – 2030	*AIM (2005)*
EPPA	✔	✕	✔	✔	Oil, Gas, Electricity	✕	Global and Regional	2004 - 2100	*Palstev, S. et al (2004)*
IMACLIM - R	✔	✕	✔	✔	Oil, Gas, Electricity	✔	Global and Regional	2001 - 2100	*Sassi, O. et al (2010)*
IMAGE/TIMER	✔	✕	✕	✕	Oil, Gas, Biomass, Electricity	✔	Global and Regional	1995 - 2100	*De Vries, B.J.M. et al (2001)*
MARKAL	✔	✔	✔	✔	Oil, Gas, Methanol, Ethanol, Electricity.	✕	Global and Regional	1990 - 2030	*Loulou, R. et al (2004)*
MERGE	✔	✔	✔	✕	Oil and Electricity	✔	Global and Regional	2000 - 2150	*Blanford, G. (2008)*
MINICAM	✔	✕	✕	✕	Oil, Gas. Biofuel, Hydrogen, Electricity	✔	Global and Regional	1990 - 2095	*Brenkert, A.L. et al (2003)*
NEMS - 2009	✕	✔	✔	✔	Oil, Gas. Biofuel, Hydrogen, Electricity	✕	Regional - United States	2007 - 2030	*EIA (2009)*
REMIND - G	✔	✔	✔	✔	Oil, Hydrogen, Electricity	✕	Global and Regional	2005 - 2100	*Pietzcker, R. et al (2010)*
SMP/IEA	✕	✔	✕	✕	Oil, Gas, Ethanol, and Hydrogen	✔	Global and Regional	2000 - 2050	*Fulton, L. and Eads, G. (2004)*
IEA MoMo	✕	✔	✕	✕	Oil, Ethanol, Biodiesel, Electricity, and Hydrogen	✔	Global and Regional	2005 - 2050	*Fulton, L. et al (2009)*
TIAM - IER	✔	✕	✔	✔	Oil, Gas, Biofuel, Hydrogen, Electricity	✔	Global and Regional	2000 - 2100	*Loulou, R. et al (2007)*
WITCH	✔	✔	✔	✕	Oil, Gas, Ethanol, Advanced Biofuels and Electricity	✔	Global and Regional	2005 - 2100	

The MERGE model is an example of an IAM where transport is included with a specific focus on vehicle type – specifically plug-in hybrid vehicles. Based on an earlier model described within Manne *et al.* (1995), Richels and Blanford (2008) extend the MERGE model to look at the role of plug-in hybrid electric vehicles (PHEVs) and other advanced climate-friendly technologies in reducing carbon emissions in the US. Blanford (2008) extends this analysis on a global scale. Reviewing the situation where upon a climate policy places a price on emissions of CO2, Blanford (2008) finds that such a policy results in the relative price difference between electricity and liquid fuels being accentuated, creating an even stronger incentive for PHEV adoption. Forecasts from a model which is not an IAM, the International Energy Agency/Sustainable Mobility Project (IEA/SMP) Transport Spreadsheet Model, have been widely cited. With the model being developed in collaboration with IEA personnel and with a focus on the period up until 2050, it has a detailed range of vehicle types across a range of transport modes and regions resulting in forecasts of energy demand and the amount of travel demanded (as implied by GDP levels and growth rates). General equilibrium models such as IMACLIM-R and EPPA, have gone further than using GDP as a measure for forecasting transport demand with the direct modelling of mobility as part of the utility function. The EPPA model developed at MIT and discussed within Paltsev *et al.* (2004) separates the modes of transport within the overall transport sector into private transport and purchased transport. Within the EPPA model the overall level of private transport is determined by the kilometres of travel demanded per year. Other models such as REMIND-G, use a nested CES structure to model a bottom-up representation of vehicle technologies and their demand for fuels.

Overall Model Structure

WITCH – World Induced Technical Change Hybrid model – is a regional integrated assessment model structured to provide normative information on the optimal responses of world economies to climate policies. Full details on the WITCH model can be found in Bosetti, Massetti *et al.* (2007), as well as in Bosetti, Carraro *et al.* (2006) and Bosetti, De Cain *et al.* (2009). With respect to climate policies, the model combines sectoral analysis of the World economy with a climate module and CO_2 emission restrictions. A reduced form climate module (MAGICC) provides climate feedback on the economic system; however in this application we will take a “cost-minimisation” approach and exclude the damage function. 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.

A dynamic optimal growth general equilibrium model, WITCH has a detailed ('bottom-up') representation of the energy sector and now a light duty vehicle transport sector as well. Belonging to a new 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 LDV transport sector. A global model, it is divided into 13 macro-regions[5]. The base year for calibration is 2005 and all monetary values are in constant 2005 USD. The WITCH model uses market exchange rates for international income comparisons. The description which follows focuses on the overall model structure and the extensions introduced to incorporate the LDV transport sector into the wider model.

Transport has been included in the 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. Demand for vehicles has been set exogenously based on the assumption that constant travel patterns correspond to given levels and growth rates of GDP and population. This assumption is important as the demand for private transport will likely continue to be high and have a strong correlation with national income, unless a significant change in the way public transport is provided occurs. This model with its current set up reviews the continuation of constant travel patterns and the constraint that this will place on the achievement of emissions reductions. The possibility of introducing a 'Travel Elasticity Switch' and a 'Vehicle-ownership Elasticity Switch' provides feedback effects which test the sensitivity of these constraints (these elasticity impacts will be reviewed in future and are not imposed within this analysis). Figure 1 shows the transportation module within the WITCH model structure. As noted, 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 (LDV Trans in Figure 1) represents the fixed proportions of operation & maintence (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

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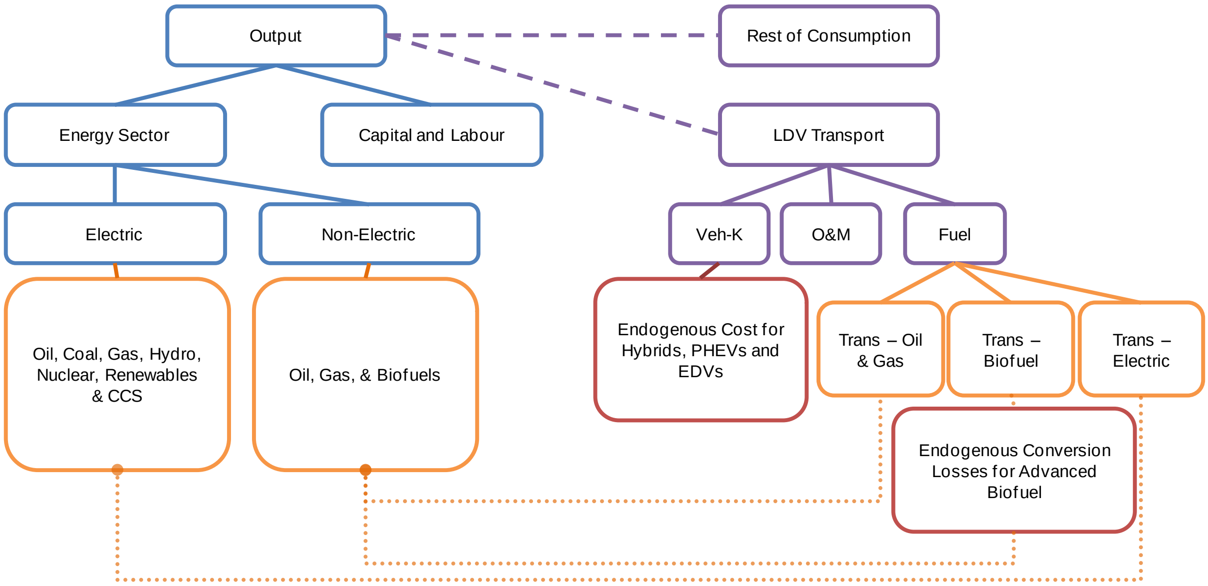
[5] The regions are USA, WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (South Korea, South Africa and Australia), CAJANZ (Canada, Japan and New Zealand), TE (Transition Economies), MENA (Middle East and South Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), SEASIA (South-East Asia), CHINA,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

results in decreases in the cost of batteries used in traditional hybrids, PHEVs and EDVs, as well as a reduction of conversion losses associated with the production of advanced biofuel.

Figure 1. The transport module



Note: transport 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 power sector.

Biofuels can either be sourced from traditional or advanced sources and are constrained to fulfil a maximum of the equivalent of an E50 fuel mixture with oil based fuels. This restriction of a maximum fuel mixture (equivalent to a 50/50 split of biofuel and oil derived fuels) has been set as higher fuel mixtures would require notable engine conversion costs and a modification of the current modelling of biofuel vehicles. With respect to traditional biofuels, we adopt conservative assumptions. The current BaU scenario includes a regional specific cap reflecting restrictions on the amount of biomass available for the supply of traditional biofuels and biodiesel – these caps have been set using Alfstad, T. (2008), a study conducted by the Brookhaven National Laboratory and prepared for the US Department of Energy. Combining the traditional biofuel and biodiesel fuel use figures from the reference case within Alfstad, T. (2008) with the WITCH model estimates for travel demand implies that without advanced biofuel, in 2020 there would be a maximum renewable fuel content in the LDV transport sector of 16.4% and and 15.7% within the EU and the USA, respectively.[6]

Advanced biofuels are sourced from within the stock of woody biomass – with the competition for the input occurring with woody biomass used in electricity. The cost of the fuel is based on a supply curve with differing grades of fuel quality and a conversion loss factor which can be modified through investments in a learning by searching process reflecting RD&D. The supply curve has been sourced from the Global Biomass Optimization Model (GLOBIOM) (Havlik et al., 2010: 3-5). WITCH and GLOBIOM have been harmonized in their basic features in order to determine the supply function for woody biomass given competing land use possibilities, such as managed forests, short rotation tree plantations, and cropland. With wood and food demand being determined by GDP and population changes, regional estimates are produced by GLOBIOM with an allowance for up to thirty-seven different crops and a minimum per capita calorie intake. The current modelling has set the cost of biofuel vehicles at the same level as petrol/diesel vehicles, with differing costs of fuel and O&M to allow for any additional costs (including conversion costs) – this allows for direct substitution of oil for biofuel with no difference in the level of vehicle investments. All other vehicle types have different levels of vehicle costs for the 2005 reference period – key indicators on the different vehicle types are displayed in Table 1Aa and 1Ab in the appendix. Vehicle costs of traditional hybrids, PHEVs and EDVs can be improved with investments that impact a learning by searching process and reflect RD&D investments.

To complete the discussion surrounding Figure 1, it should be noted that the electricity for use in EDVs can be sourced from the sources within the electric sector and this allows the model to determine the electricity source that EDVs are associated with. The range of electricity sources available to partially fuel PHEVs and completely fuel EDVs include a series of traditional fossil fuel-based technologies and low carbon options. The fossil fuel-based technologies include natural gas and pulverised coal power plants. Coal-based electricity can be generated using integrated gasification combined cycle production with carbon capture and sequestration. Low carbon technologies include hydroelectric and nuclear power, renewable sources (such as wind turbines) and a breakthrough technology (such as concentrated solar power).

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

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[6] This constraint on biofuels makes it impossible to achieve the renewable fuel targets legislated within the US and EU, unless advanced biofuels come online.

complete list of variables is reported in the appendix within table 2A. 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.

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

Equation 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 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.

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

The aggregate level of consumption net of transport expenses, is gross consumption subtracted by the cost for private transportation, including investments in LDVs, I_{ldv}, investments in research related to battery and/or advanced biofuel technologies, RI_{TECH}, operation and maintenance of the vehicles, $O\&M_{ldv}$, and the fuel costs, $FE_{ldv,j}$, of each fuel j.

$$C(n,t) = CG(n,t) - \sum_{ldv} I_{ldv}(n,t) - RI_{TECH}(n,t) - \sum_{ldv} O\&M_{ldv}(n,t) - \sum_{ldv,j} FE_{ldv,j}(n,t) \tag{3}$$

Starting with the level of investments in vehicles during time period one, equation 4 sets the subsequent period's capital stock of LDVs, K_{ldv}, equal to the level of capital remaining after depreciation[7] and the additional capital implied by investments undertaken at the prevailing investment cost of vehicles, SC_{ldv}. The amount of capital for private transportation in each period for each region is constrained by the demand on mobility (a function of GDP and other factors, as described in the previous section).

$$K_{ldv}(n,t+1) = (1-D)\big(K_{ldv}(n,t)\big) + (I_{ldv}(n,t)/SC_{ldv}(n,t)) \tag{4}$$

The amount of fuel demanded by each vehicle is defined by the average fuel efficiency of the vehicle ($AFE_{ldv,j}$), fuel efficiency improvement, $FEI_{ldv,j}(t)$, and the amount of kilometres travelled per year[8]. Fuel efficiency improvements are time dependent and assumptions on the dynamics are detailed later on in the paper (refer to the discussion surrounding figure 5). The average fuel efficiency variable has been set to the 2005 level for each vehicle type.

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[7] 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.

[8] Note that adjustment of the $AFE_{ldv,j}$ variable needs to occur in cases where the amount of kilometres travelled per year is adjusted. Within this model this occurs using an adjustment factor that is a function of time and the kilometres travelled in the corresponding time period.

The range of vehicles, *ldv*, 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. These include traditional combustion petrol fuelled vehicles (TCARS), diesel fuelled vehicles (DIESEL), traditional petrol fuelled hybrid vehicles (TR_HYBRID), diesel fuelled hybrid vehicles (D_HYBRID), first generation/traditional biofuels fuelled vehicles (TR_BIOFUEL), biodiesel fuelled vehicles (BIODIESEL), advanced biofuel vehicles (ADV_BIOFUEL) and natural gas fuelled vehicles (LPG). In addition to these vehicle types, which existed in some shape or form in 2005, we have also incorporated plug-in hybrid vehicles (PHEV) and electric drive vehicles (EDV) to represent the types of vehicles being introduced onto the market in the years around 2010 – such as the Chevrolet Volt and the Nissan LEAF. For each of these categories we have set different fuel economy and vehicle cost levels (as summarised within table 1Ab) and while the model is solved with the potential to utilise any of these vehicle options, for the sake of simplicity we will present the results in terms of traditional combustion engine vehicles (shortened to TCE and made up of the aggregate of the TCARS and DIESEL categories), HYBRID (as the aggregate of TR_HYBRID and D_HYBRID), as well as BIOFUEL (as the aggregate of TR_BIOFUEL and BIODIESEL). Within the sections that follow – ADV_BIOFUEL, PHEV and EDV will be subject to no aggregation.

Technological change is endogenous in the model and it affects both the cost of batteries for electrified vehicles and that of conversion of advanced 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) and is accumulated with increased investments ($RI_{TECH}(n,t)$) and a 'standing on the shoulders of giants' effect based on the previous level of capital.

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

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 (SC_{EDV}) [9]and the cost of advanced biofuel (FE_{ADVB}).

$$\frac{SC_{EDV}(n,t)}{SC_{EDV}(n,1)} = \left(\frac{(RK_{EDV}(n,t)+RSpill_{EDV}(n,t-l)}{RK_{EDV}(n,1)}\right)^{-LR} \tag{6}$$

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

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[9] 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 so easily tradable we assume that the cost in each country is affected by the research cumulated in that country up to that period plus the incremental amount of research accumulated by the sector innovation leader, $RSpill_{ADVB}$, though with a lag time that accounts for the advantage of being the first mover. The model assumes that the transfer of technology can occur rapidly with 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[10] and the support by the European Investment Bank to produce electric batteries at the Nissan Sunderland Plant from early 2012. (EIB, 2011) Schwoon (2008) notes that the car industry is characterised by learning spillovers due to the prevalence of technology clusters and common sub-contractors. Within the developing country context Ivarsson and Alvstam (2004) review a Volvo Trucks' assembly plant in India and note that foreign transnational companies may provide local suppliers with technological assistance or follow a corporate strategy of 'follow sourcing' where operations are established close to their established customers.

Calibration and Data

Demand for Vehicle Ownership

Private transport is a good description of the majority of the existing LDV stock and typically represents a range of personally owned and consumed automobiles which differ across fuel type and consumption. The approach taken in this paper is to set the demand for the number of vehicles per year (based on GDP levels/growth rates) while assuming a given level of kilometres travelled per annum. The amount of kilometres travelled per year differs across regions to represent differences in congestion levels, preferences, as well as the availability of public transport and other modes of travel, such as 2-wheeled vehicles. This approach is based on literature on regularities of travel demand (such as Schafer (2000)) and the assumption that once an investment in a LDV has been made then it will be used to its full potential, subject to constraints such as the amount of time available for travel and the costs of operating the vehicle. The amount of kilometres driven in each region has been set to the average distance travelled today subject to prevailing levels of congestion and travel preference between private and public transportation.

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[10] 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)

Projections of the amount of vehicle ownership within each region has been established using a similar approach to that employed by the International Energy Agency/Sustainable Mobility Project (IEA/SMP) Transport Spreadsheet Model, which in turn was based on the work of Dargay and Gately (1999). [11] Using population and GDP projections harmonized with that of the WITCH model, we have applied the prescribed logistic function of car ownership for each WITCH macro region to the regional level of per capita income and the projected income growth between the 5 year periods. Figure 2 shows the estimates of LDV ownership for selected regions from 2005 to 2100. The global increase leads to the number of vehicles estimated for 2050 being approximately three times larger than the 2005 level. This global level is approximately 15% higher than the corresponding reference case presented by the World Business Council for Sustainable Development in 'Mobility 2030: Meeting the Challenges to Sustainability' which is based on the International Energy Agency/Sustainable Mobility Project (IEA/SMP) Transport Spreadsheet Model (WBSCD, 2004). Table 2 compares the levels of LDV ownership in the WITCH model to the levels reported for the IEA/SMP model within Fulton, L. and Eads, G. (2004) and the levels reported for the IEA Mo Mo model within Fulton et al. (2009).

In 2050 the levels of vehicle ownership in the WITCH model are 48% higher than 2005 levels for the OECD. This is in comparison to levels that are eight times higher for the non-OECD. By 2050 the aggregate number of light duty vehicles in non-OECD countries will be 89% larger than that in OCED countries. Significant growth in the number of vehicles occurs within non-OECD nations from 2050 onwards. The WITCH model estimates related to the number of vehicles in the OECD and non-OECD are in line with the SMP/IEA model, as well as both the 'Reference Case' and 'BLUE Map' scenarios presented for the IEA Mo Mo model. In these models, growth in vehicle ownership in the OECD results in a case where the 2050 level is approximately 40-41% higher than the 2005 level. However, their global projection is 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.

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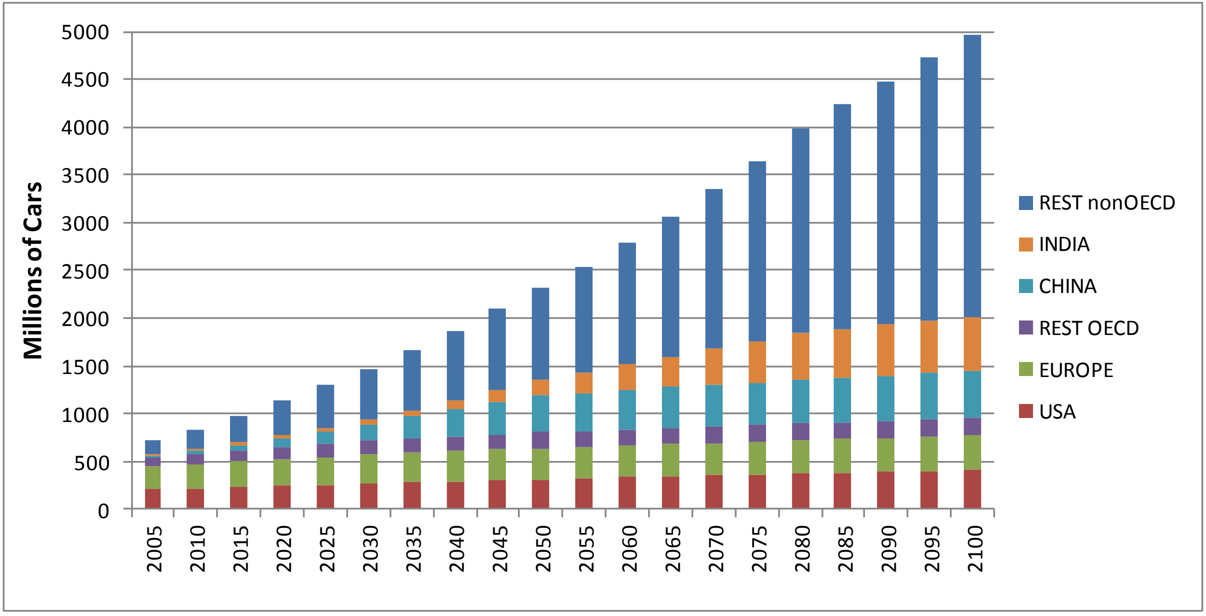
[11] Parameters are reported in Table 3A of the appendix.

Figure 2. Number of LDVs across selected regions (millions of vehicles)



Source: WITCH model projection

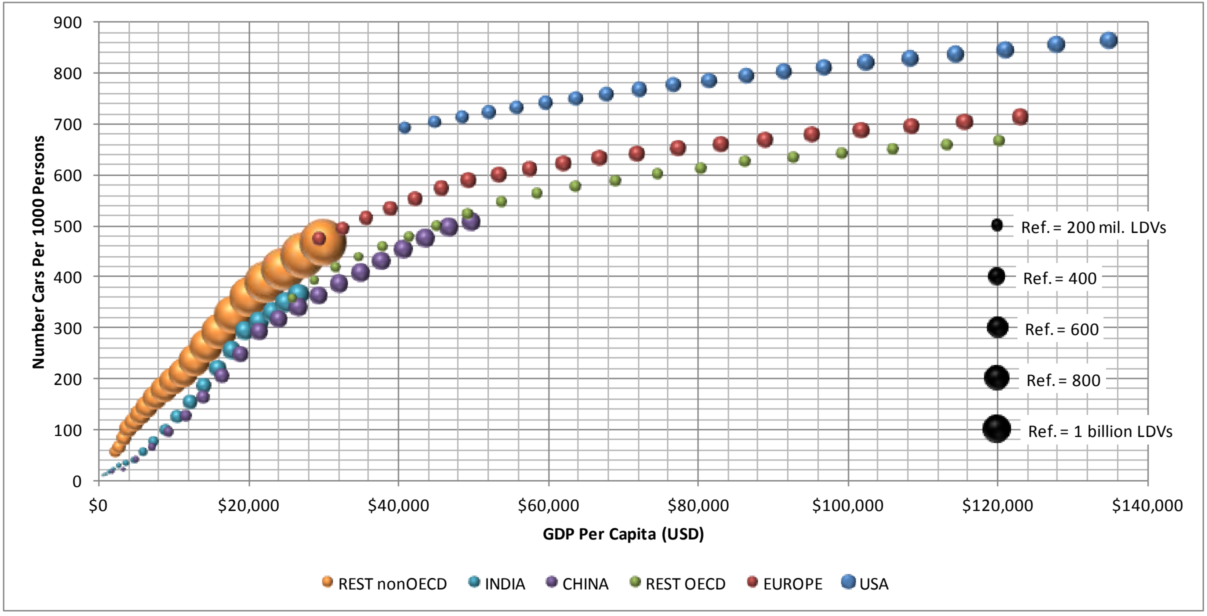
Table 2. Transportation Models Vehicle Forecasts

MODELS	REGION	Millions LDVs 2005 No. (No. times higher than 2005)	Millions LDVs 2030 No. (No. times higher than 2005)	Millions LDVs 2050 No. (No. times higher than 2005)	GLOBAL / REGIONAL FOCUS	FORECAST TIMELINE	REFERENCE
SMP/IEA	OECD	565.8 (0.00)	727.7 (1.29)	792.5 (1.40)	Global and Regional	2000 - 2050	*Fulton, L. and Eads, G. (2004)*
	Non-OECD	178.5 (0.00)	560.9 (3.14)	1216.9 (6.82)			
	Global	**744.3 (0.00)**	**1288.6 (1.73)**	**2009.4 (2.70)**			
IEA MoMo	OECD	576.0 (0.00)	748.0 (1.30)	813.0 (1.41)	Global and Regional	2005 - 2050	*Fulton, L. et al (2009)*
	Non-OECD	173.0 (0.00)	618.0 (3.57)	1331.0 (7.69)			
	Global	**749.0 (0.00)**	**1367.0 (1.83)**	**2144.0 (2.86)**			
WITCH	OECD	542.2 (0.00)	713.6 (1.32)	804.6 (1.48)	Global and Regional	2005 - 2100	
	Non-OECD	188.5 (0.00)	759.5 (4.03)	1521.7 (8.07)			
	Global	**730.7(0.00)**	**1473.2 (2.02)**	**2326.3 (3.18)**			

Figure 3 shows the trend in the number of vehicles per 1000 person in comparison to the level of GDP per capita. The size of the bubbles reflects the total level of vehicle ownership (these bubbles are in reference to the black bubbles ranging from 200 million EDVs to 1 billion EDVs). With the USA and Europe having the highest starting points on the basis of number of vehicles per 1000 persons, we can see that these regions have a relatively constant growth rate from 2010 to 2100. Rapid increases in the level of vehicles projected for China is reflected by a notable increase over the 2005 to 2100 period which results in a situation where the vehicle ownership and per capita income levels in 2100 surpasses the 2005 level of Europe. Over the same period India surpasses the 2005 level of ownership per capita for the rest of the OECD. The rest of the non-OECD reaches levels similar to that of Europe in 2005. While China shows considerable growth, the combined case of India and the rest of the non-

OECD cannot be ignored with large increases in vehicle ownership. Indeed, the number of vehicles in the rest of the non-OECD surpasses the number of vehicles in the combined OECD by 2045. In addition, the amount of vehicles in the rest of the non-OECD remains higher than the combined India and China total in all periods from 2005 to 2100 by at least 79%.

Figure 3. Vehicle Diffusion across Selected Regions from 2005 to 2100 – Number Cars per 1000 Persons (compared to GDP per capita)

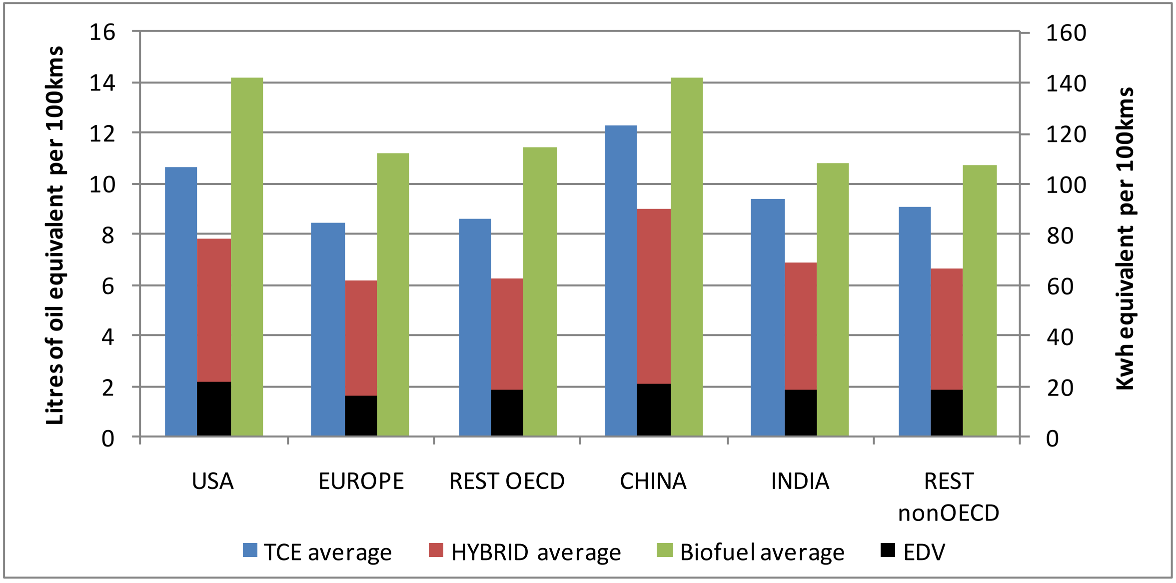


Vehicle Specifics

Having set the level of vehicle ownership within each region on the basis of GDP, the model solves for the optimal mix of vehicles based on key variables, such as the fuel efficiency of the vehicle, the vehicle cost, operation and management (O&M) costs, the type and cost of fuel used, as well as the total amount of kilometres driven per annum. These factors determine the fleet mix. Base year values for kilometres driven per annum, vehicle stock, vehicle cost and O&M cost are shown in Table 1Aa and 1Ab in the appendix. Figure 4 reviews the fuel demand for the key vehicle categories based on 100 kilometres of travel and is presented as both litres of oil equivalent and kilowatt hours. Upon reviewing the differences in annual fuel demand it should be noted that regional differences in fuel efficiency and kilometres driven have been set with an allowance for a predisposition towards different size vehicles, the quality of roads, and the levels of congestion expected to exist across the key regions. Note that these regional differences have been set using an example vehicle for that category and the application of regional indices. The regional indices have been set using data from the IEA/SMP model, with slight modifications to match the 2005 oil use in some regions. Biofuel vehicles represent unconverted TCE vehicles with an oil/biofuel fuel mix, while the HYBRID and

EDV vehicle types are based on the Toyota Prius and the Nissan Leaf. In summary, the variables within the model have been set using medium sized vehicles with adjustments in fuel efficiency levels for regional differences and includes predispositions to larger vehicles (such as in the USA).

Figure 4. Fuel Efficiency of Key Vehicle Types in 2005 for Selected Regions



All of the factors mentioned are important in determining the overall mix of vehicles and tend to be key determinants in the introduction of different vehicle types. Fuel efficiency and the kilometres driven impact upon the fuel load; and the vehicle cost and the cost of fuel are also important. Externalities, when priced or accounted for in specific scenarios will also affect the fleet structure.[12] As total cost is the driver for changes between vehicles within the model, we now focus on how these key assumptions change in the model over time to reflect changes in technologies, their costs and the general likelihood of the successful commercialisation of the different vehicle options.

Figure 5 sets out the fuel efficiency improvements (FEI) scenarios which will be applied to review the sensitivity of the results to the projected levels of fuel use for each vehicle. Mild fuel efficiency improvement (Mild FEI) and strong fuel efficiency improvement (Strong FEI) are the two main dynamics considered in the model; the rates show how much fuel is needed in comparison to the base year to travel the same distance and applies to all vehicle types. The Strong FEI scenario has been set to correspond to the World Energy Outlook 2006 Policy Scenario figure for the OECD in 2030 (represented as the 'WEO Policy Scenario' point in Figure 5). The Strong FEI scenario also lies

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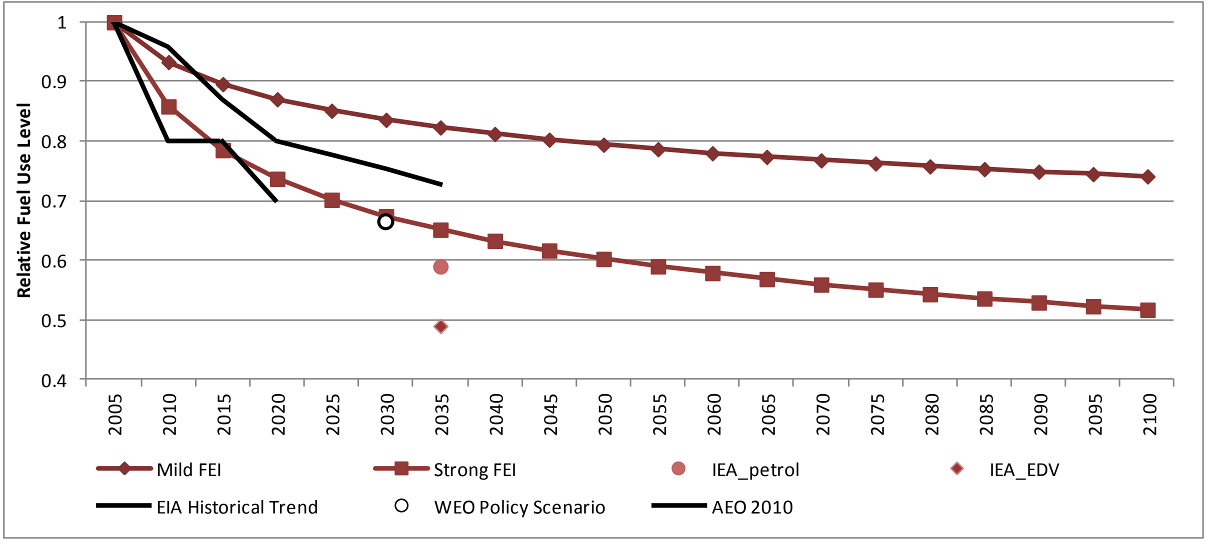
[12] While many additional factors and characteristics not related to costs affect consumers' choice across vehicles, we will only be able to capture this with the inclusion of the VES (specified in equation 10 and to further reviewed in future work) rather than through specific endogenous emerging properties.

within the historical trend for the US between 1983 and 2001 ('EIA Historical Trend' in Figure 5) and the Annual Energy Outlook 2010 Reference case ('AEO 2010' in Figure 5). As a conservative scenario, the Mild FEI case has been set at half the rate of FEI of the Strong FEI scenario. In Figure 5 we also portray data on projected FEIs reported in an expert elicitation conducted by the International Energy Agency (IEA) and discussed within IEA (2009a) and IEA (2009b). The estimates for petrol vehicles and EDVs are represented as dots and denoted as 'IEA – petrol' and 'IEA – EDV'. These two reference points are used to test the robustness of results in the scenario analysis performed later in the paper (refer to table 3 – scenario 'FEI Cost' for further information).

Figure 5. Fuel Efficiency Improvements (FEI) Scenarios



Note: A value of 1 in 2005 represents the fuel efficiency level of the vehicle in that period – with decreases across periods showing the change of efficiency levels over time for all vehicles. Mild and Strong FEI refers to FEI scenarios used within this study where fuel efficiency is modified. These are then compared to FEI estimates based on historical data from the EIA[13] for the USA and scenarios for future periods from the AEO[14].

In addition to that of FEI, the dynamics of the cost of vehicles is crucial and these two factors represent technological change in the basic version of the model. All vehicles within the model for which cost dynamics are exogenous (which are all vehicles – except for traditional hybrid, PHEVs and EDVs) have a decrease in the cost set to approximately one percent per year with a price floor of $24100 – which corresponds to the model's initial price for petrol fuelled vehicles in 2005. Figure 6 compares the vehicle cost decreases within the model to the historical trend for the USA between 1981 and 2006 in terms of the ratio of the cost of vehicles and per capita GDP. The historical data adapted using a source from the US Dept of Energy's Vehicle Technology Program website (DOE

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[13] EIA fuel efficiency source used to calculate FEI estimate entitled 'EIA Historical Trend': EIA Residential Transportation Historical Data Tables.

[14] AEO fuel efficiency source used to calculate FEI estimates entitled 'AEO 2010': US EIA (2010) – Annual Energy Outlook 2010.

(2008)), shows a decrease in slope of the fitted curve of 0.1985 per five year period, while the WITCH model assumes decreases in slope of between 0.0362 and 0.1080 over five year periods between 2005 and 2030. This confirms that the model's base case cost scenario can be deemed to be conservative with regards to historical data. As shown in Figure 7, when assuming endogenous R&D, we are still in line with conservative assumptions and the sensitivity of the results will be reviewed using a scenario based on a sharper decrease in the cost of vehicles using battery based technologies (for further information refer to table 3 – scenario Rapid Imp). In the case where endogenous technical change is accounted for, the cost of traditional hybrids, PHEVs, EDVs and conversion of advanced biofuels is based on the learning by searching process driven by RD&D investments as described in equation 6 and 7.

Figure 7 compares the price of EDVs under an exogenous technical change and endogenous technical change scenarios. Within the exogenous scenario there is one prevailing world price for EDVs, while the endogenous scenario has heterogeneous prices across regions (which are also reflected in the price of traditional hybrids and PHEVs). When endogenous technical change is unspecified we use the basic assumptions that are consistent with the approach used for the rest of the vehicle types, i.e. a decrease in the cost set to approximately one percent per year with a price floor of $24100. The results of the model reviewed in section 3 and 4 will show that the pace of cost improvements of alternative transportation modes affects results crucially. We review alternative cost scenarios for advance biofuels and EDV by changing learning rates. For example, we test the effect of cost improvements in batteries that are in line with the historical price improvements in traditional cars as shown in Figure 6. This fast pace costs improvements was due to many effects, from economies of scale, to learning by doing and by researching. The implied learning rate of this extremely optimistic scenario is 0.50. With a starting value of $58607 in 2005, the case of a learning rate of 0.10 results in the price of EDVs decreasing to about $41000 in 2050, with a learning rate of 0.20 the price is about $32000 and the extreme case of 0.50 results in a price of EDVs in 2050 of about $25000. Not shown in Figure 7, but still included within the endogenous technical change formulation is the case of advanced biofuel conversion. With a starting value of 44% in 2005, the case of a learning rate of 0.10 results conversion losses decreasing to 40% in 2020, with a learning rate of 0.20 the conversion loss is 35% and the extreme case of 0.50 results in a conversion loss in 2050 of about 26%.

Figure 6. Ratio of Vehicle Purchase Price and GDP per capita for the period 1981-2006 in the USA (Historical) and for the WITCH base scenario in the period 2005-2030 for Traditional Combustion Engine Vehicles and Electric Drive Vehicles.

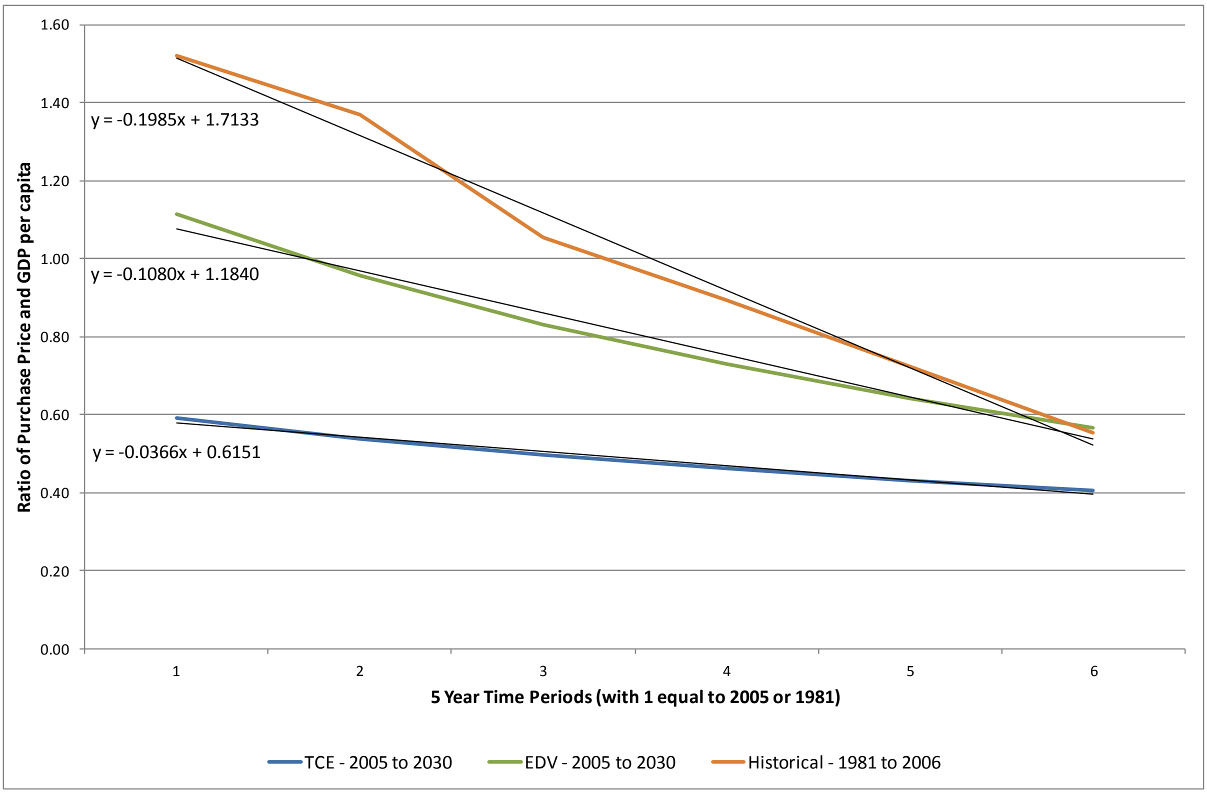
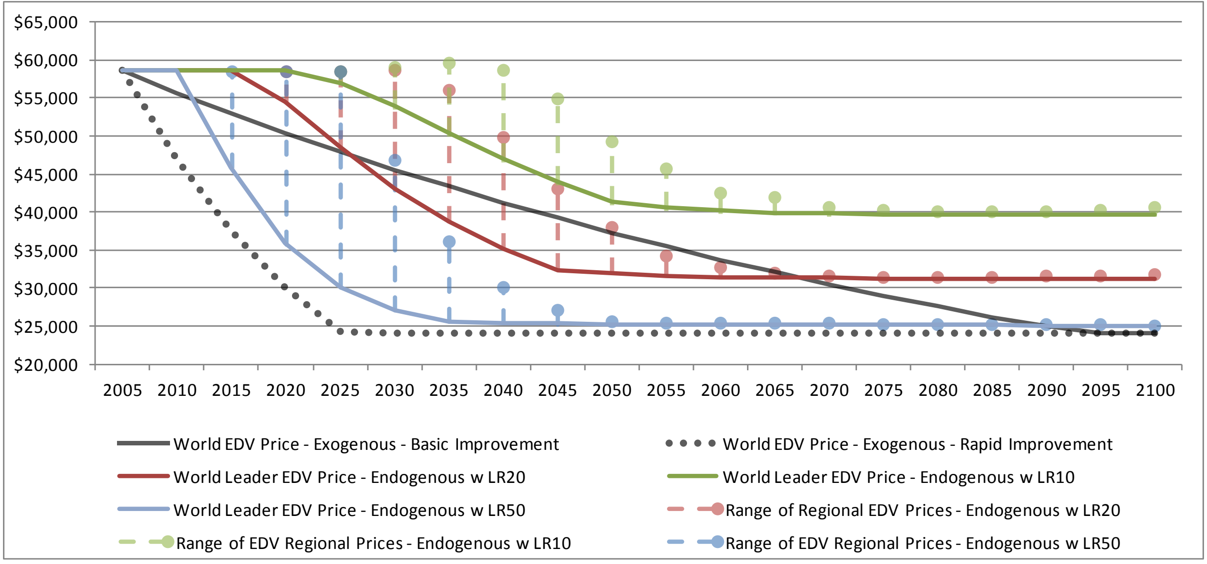


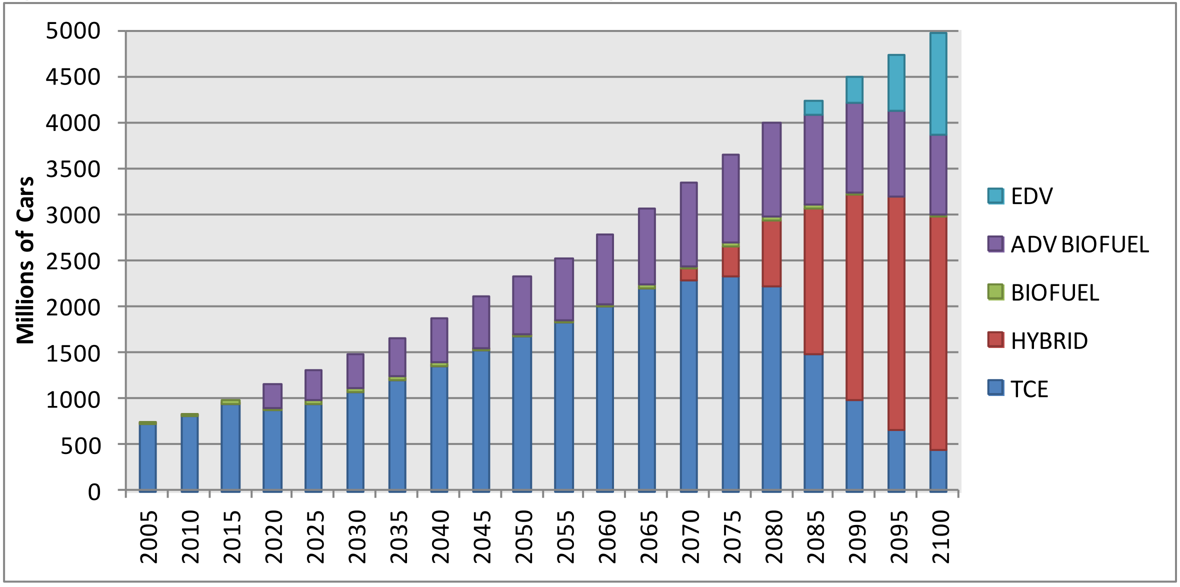
Figure 7. Price of Electric Drive Vehicles – Exogenous and Endogenous Scenarios



Section 3 – LDV Transport Sector Dynamics in a no climate policy scenario

This section presents the major dynamics within the LDV transport sector under a Business-as-Usual scenario (BaU) with endogenous technical change in advanced biofuel conversion and battery technologies.[15] Within the BaU no consideration is given to the carbon content of fuel, hence traditional combustion engine vehicles tend to dominate until the late part of the century. Figure 8 shows the global distribution of vehicles across the main vehicle classes with traditional combustion engine vehicles dominating the BaU scenario and advanced biofuels entering the fuel mix to supplement both diesel and petrol based fuels. Even without any cost attached to carbon, the introduction of hybrid vehicles occurs in the post 2070 period when the cost of purchasing and running a hybrid vehicle becomes equivalent to that of a traditional vehicle. Electric drive vehicles become commercially viable and are introduced post 2085 when costs are sufficiently reduced to make them affordable. It is at this point, that a reminder should be made that within this model, consumption and income are determined at a macroeconomic level and as such the effects of income stratification on vehicle profile are not considered. Results represent the dominant market choices and do not include the possible existence of fringe vehicles that may be present but continue to be a small proportion of the market. In the BaU, the least costly mix of vehicle and fuel will determine the composition of vehicles, while in reality there will be a stratification of spending patterns based on preferences and the income distribution within the economy. Accordingly, the variables within the model and described in section 2 have been set using medium sized vehicles with adjustments in fuel efficiency levels for predispositions to larger vehicles (such as in the USA).

Figure 8. Global BaU Vehicle Distribution with Strong Fuel Efficiency Improvement



Source: WITCH Model Projection

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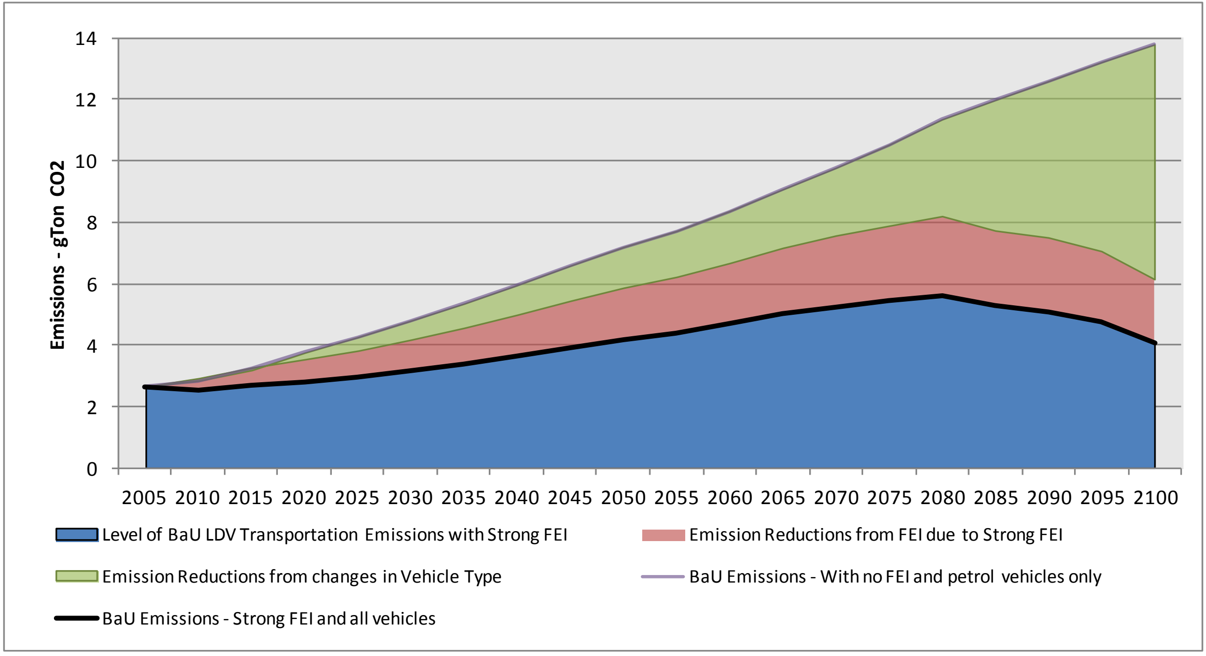
[15] In the BaU we assume that no climate policy is implemented to constrain GHGs emissions.

In establishing the basic BaU scenario, the amounts of emissions which prevail are discussed and the impact of FEIs highlighted. Figure 9 reports emissions from the transport sector both in absolute terms and as share of total fossil fuel emissions. The figure reveals how fuel efficiency improvements and changes in vehicle types impact the amount of emissions from the LDV transport sector. The key assumption here is that advances in fuel efficiency and battery technology continue irrespective of climate policy action, as they are also driven by the utilization of alternative fuel supplies and local considerations of air pollution and energy security.

Figure 9. Global BaU Emissions and Emissions Reduction

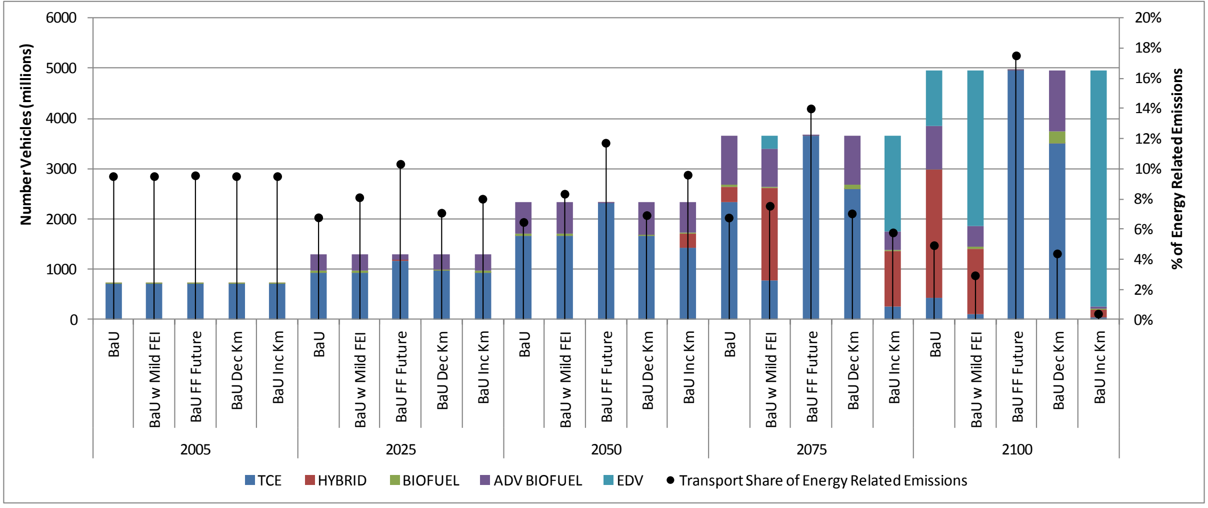


Note: Emission reductions from changes in vehicle type represent the emissions reduced by moving away from traditional petrol vehicles with no fuel improvements applied. Emission reductions from FEI are those that correspond with the Strong FEI scenario and the vehicle distribution shown in figure 7.

Obviously, sources of uncertainty when making projections so far in the future are many. We explore different dimensions that could influence the main results by studying alternative scenarios. In particular the effect of fuel efficiency assumptions is tested by running a baseline scenario where fuel efficiency follows the mild path (BaU Mild FEI) as shown in Figure 5. The potential of a failure for alternative transportation modes to come online due to infrastructure lock-in or other inefficiencies is tested through a dedicated baseline scenario (BaU FF Future). The effect of radical changes in number of kilometres driven due to changes in consumer behaviours and investment in public transportation modes is review through the (BAU Dec Km) scenario. With an increase in the average number of miles driven within the USA between 1985 and 2005 being estimated by the ‘Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025’ as being at 1.2% per year, the BaU Dec Km and BaU Inc Km scenarios apply this annual rate of change as an decrease or an increase, respectively.

By analysing these alternative futures we see that after 2015 emissions would start to differ wildly across scenarios. BaU LDV transport emissions rise from 2.7 gigatonnes of CO2 in 2005 to 5.3 gigatonnes of CO2 in 2085 and then decreases to 4 gigatonnes of CO2 in 2100. Compared to the FF Future scenario we can attribute emission decreases to fuel efficiency improvements and vehicle fleet changes – these emission decreases are plotted in Figure 9. Figure 10 compares the vehicle distributions of a range of BaU scenarios. In comparison to the BaU, the Mild FEI scenario has a higher level of emissions attributed to the transport sector (due to more energy intensity per vehicle) until after 2075 when fuel use and emissions are decreased with the earlier introduction of EDVs. By 2100, the proportion of energy used in LDV transport is similar to the BaU as there is a larger amount of relatively fuel efficient EDVs. The fossil fuel future (FF Future) scenario is that where the TCE vehicle which exists in 2005 continues with no FEIs until the end of the century. As a result, this scenario is attributed with global LDV transport emissions of about 13.8 gigatonnes of CO2 in 2100 and LDV transport accounts for 18% of energy related emissions in 2100. This is in contrast to levels between 3% and 5% in the BaU & Mild FEI scenarios**.** Altering the number of kilometres travelled per annum impacts the results by either delaying or encouraging investments in breakthrough technologies. Starting from 2015, the BaU Inc Km scenario implies a doubling of kilometres travelled by 2070 and this coincides with a more intense introduction of EDVs between 2050 and 2075 due to higher fuel prices.

Figure 10. Vehicle Distribution Compared to BaU



BaU: Basic assumptions with no climate policy; BaU w Mild FEI: Fuel efficiency follows the Mild trajectory; BaU FF Future: TCE vehicles continue with no FEIs; BaU Dec Km: Kilometres travelled per annum decreases; BaU Inc Km: Kilometres travelled per annum increases.

Section 4 – LDV Transport Sector Dynamics in a Climate Stabilisation Scenario

Let us now assume that a climate policy aimed at stabilizing world concentrations of GHGs at 550ppm CO_2-eq by 2100 is in place from 2025 onwards. The key objective is to study the role of the transportation sector in affecting stabilization policies, for this reason we do not really look into credible policies in terms of participation or timing of action, rather we concentrate on the most efficient policy and see how it would be affected by alternative transportation scenarios. 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[16]. Regions receive emission allowances that can be traded in an international carbon market. All sectors, including transportation, are capped. We start by discussing a basic stabilization scenario, we will then review additional scenarios where key assumptions and underlying parameters are modified to test the robustness of results and discuss the major drivers of change. Descriptions of these scenarios are presented in Table 3.

Table 3. Description of Stabilisation Scenarios

Scenario Name and Acronym	*Brief Description*
Basic Stab Scenario (STAB)	All vehicles within the model are available and the Strong FEI scenario applies.
No Electric Drive Vehicle (No EDV)	This scenario assumes that no major breakthrough in the cost and efficiency of batteries will occur during this century.
Lower improvements in fuel efficiency improvements (Mild FEI)	All vehicles within the model are available and the Mild FEI scenario applies.
FEI Cost Scenario (FEI Cost)	This scenario reviews the maximum potential for FEIs and the associated costs of achieving this level of efficiency improvement. Based on a study completed by the IEA and discussed in the World Energy Outlook 2009. Endogenous technology changes do not apply.
Lower learning rate (LR 10)	All vehicles within the model are available, the Strong FEI scenario applies and the learning rate applied to the learning by searching function is set equal to 0.10 (rather than 0.20).
Rapid improvements in battery costs (Rapid Imp)	All vehicles within the model are available, the Strong FEI scenario applies and the cost of HYBRIDs, PHEVs and EDVs decreases at a higher rate (matching historical data plotted in figure 6). The implied learning rate is 0.50.

Figure 11 shows the global distribution of vehicles across vehicle type within this basic stabilization scenario (STAB). Traditional combustion vehicles with different fuel mixtures dominate until 2035-2045, when traditional hybrids and then electric drive vehicles significantly enter the market to

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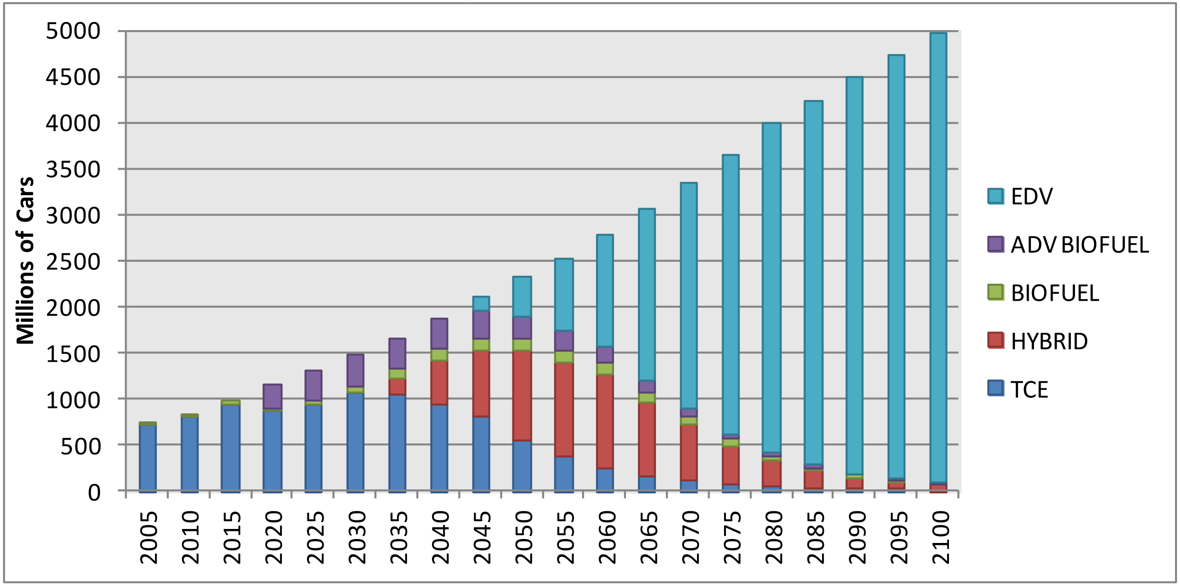
[16] Although this is unlikely to be the outcome of future climate negotiations, it is a useful assumption for the objective of the present analysis as we want to abstract from the burden sharing issues.

become the most dominant types of vehicles existing within the LDV transport sector[17]. Underlying the global trend are investments which drive innovations in battery technologies used in hybrids and EDVs. China and the USA tend to drive these investments and introduce these advanced vehicles before the rest of the world. Within OECD regions there is a notable trend for biofuels to supplement oil based fuels until the mid-century when electric drive vehicles and traditional hybrids tend to be introduced. The USA and China have the earliest and strongest switch towards traditional hybrids, with Europe and the rest of the OECD introducing traditional hybrid vehicles in the next period. China adopts EDVs in 2045, with the USA following in 2050 and KOSAU following one period behind. A staggered trend across regions and the initial introduction of hybrids is driven by delayed spillovers in research knowledge and cost, and hence the cost of a new vehicle and its annual fuel cost, related carbon cost and O&M cost are shown in figure 12.

Figure 11. Global Vehicle Distribution under a 550 ppm stabilization scenario and assuming Strong Fuel Efficiency Improvement and all technologies are unconstrained



Source: WITCH Model Projection

Figure 12 shows the cost of three key vehicle types across six different time periods for the USA and compares these to that vehicle's share of global sales within the LDV transport sector. A decrease in the share of TCE vehicles within 2020 and 2030 is due to the use of biofuels as an alternative fuel source. In 2050 a further decrease occurs with the introduction of hybrids and EDVs - which in the US are fuelled primarily by electricity from woody biomass with IGCC. The introduction of EDVs in 2045 is in light of higher vehicle costs, but this is offset by considerable emissions reduction possibilities in comparison to the alternatives. After 2045 there is a gradual move towards battery

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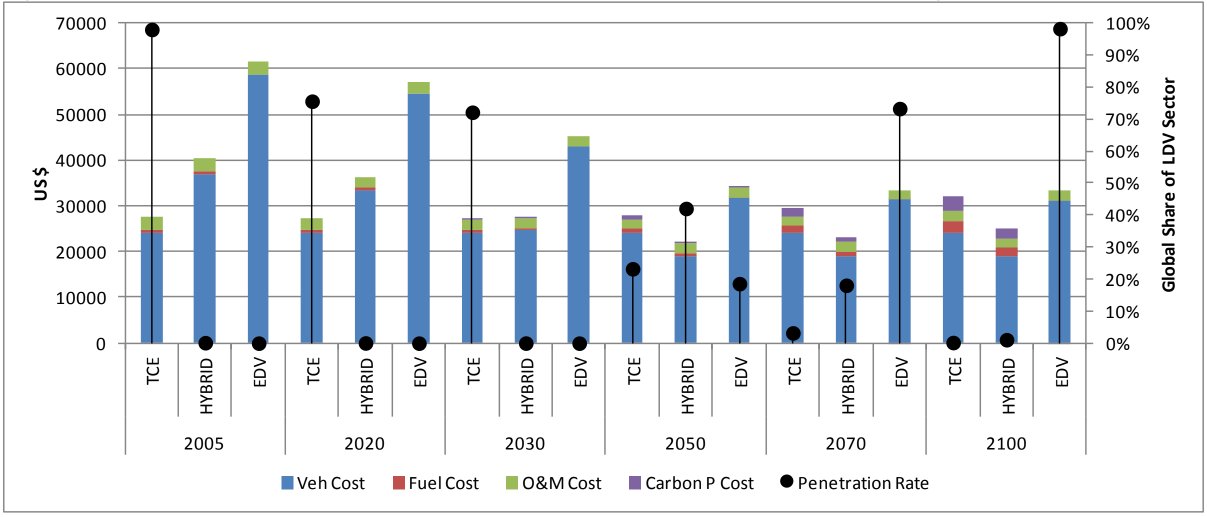
[17] Note that upon reviewing the vehicle shares it must be remembered that these results should be interpreted as representing the dominant market choices.

fuelled technologies with EDVs dominating worldwide in 2100. Cost is a key determinant in the infiltration of traditional hybrids rather than PHEVs, and PHEVs are not preferred to the introduction of EDVs when the cost is low. Note that within figure 12, the total costs of EDVs are only shown once the source of the electricity has been allocated by the model. The model selects the accompanying source of electricity with which EDVs are fueled and hence fuel costs can only be plotted from 2050 onwards. In 2100, the amount of electricity used by the LDV transport sector is approximately 11% of the total electricity generated. With strong FEIs, this is a moderate amount of electricity as it is equivalent to 37% of the electricity generated in 2005. Figure 12 shows that for the USA, the cost of carbon and the price of oil leads to the cost of employing a TCE vehicle increasing in the latter half of the century.

Figure 12. Cost of New Vehicle – Cost of a new vehicle in the USA and % share of global vehicle



The type and amount of fuel used in satisfying electricity demand from EDVs is an important consideration. Figure 13 compares the amount of fuel used in the BaU scenario with that of this basic stabilization scenario and shows that the decarbonisation of the LDV transport sector in the latter half of the century is associated with the use of renewables and woody biomass with CCS technology. While prior to 2040 similar fuel use to that of the BaU occurs, the amount of fuel used by the LDV transport sector is notably lower in the STAB scenario post 2050 corresponding with approximately 34% of the BaU level in 2100. With respect to the use of oil in the transport sector as a percentage of the total use of fuel in all sectors of the World economy, LDV transport oil consumption makes up approximately 23% of total oil use in 2005, decreasing to 14% in 2025, and then increasing to 17% in 2045. Matching the decarbonisation of the LDV transport sector in the latter half of the century the share of total oil employed within the LDV transport sector then declines from 17% in the year 2045 to 1% in 2100. To close the review of this basic STAB scenario, emissions are focused upon within figure 14 with BaU emissions compared to those from the STAB scenario. The transportation sector starts to contribute to decarbonization later than other sectors. From mid century onward, emissions rapidly decrease to the extent that LDV transportation become a carbon free sector by 2080. From there onwards transportation becomes a net sink, due to complete electrification coupled with bio-energy and CCS power production technologies.

Figure 13. Global Fuel Use Transport Sector – BaU Compared to STAB

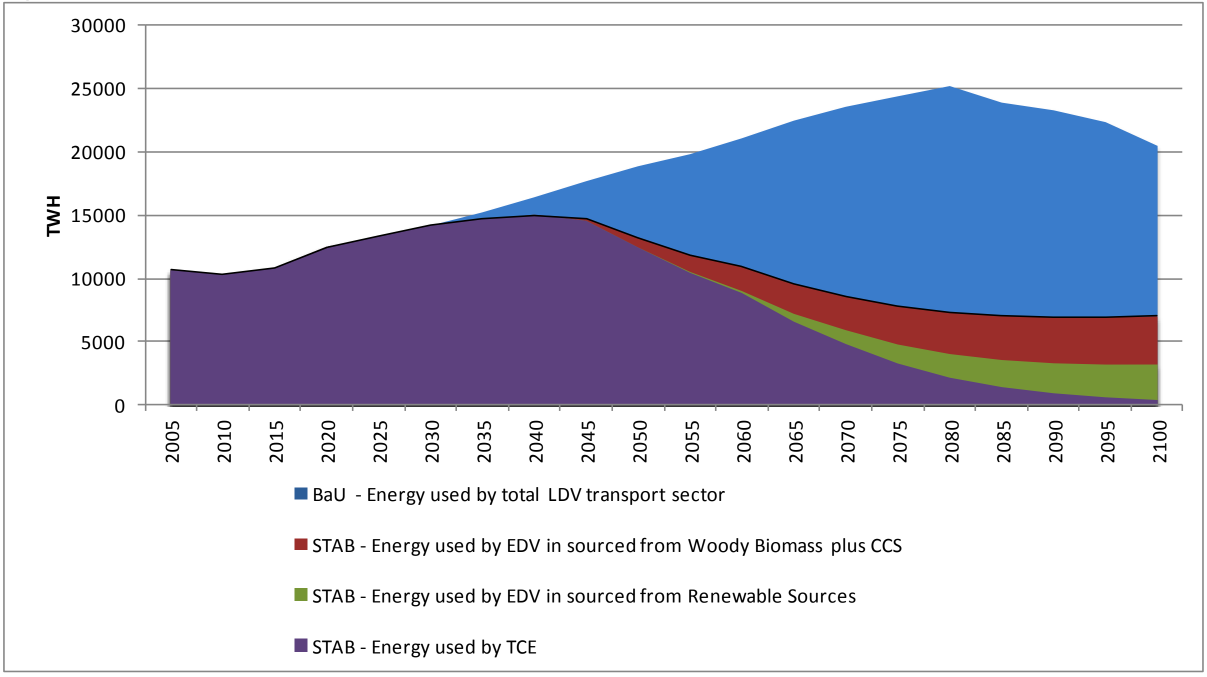
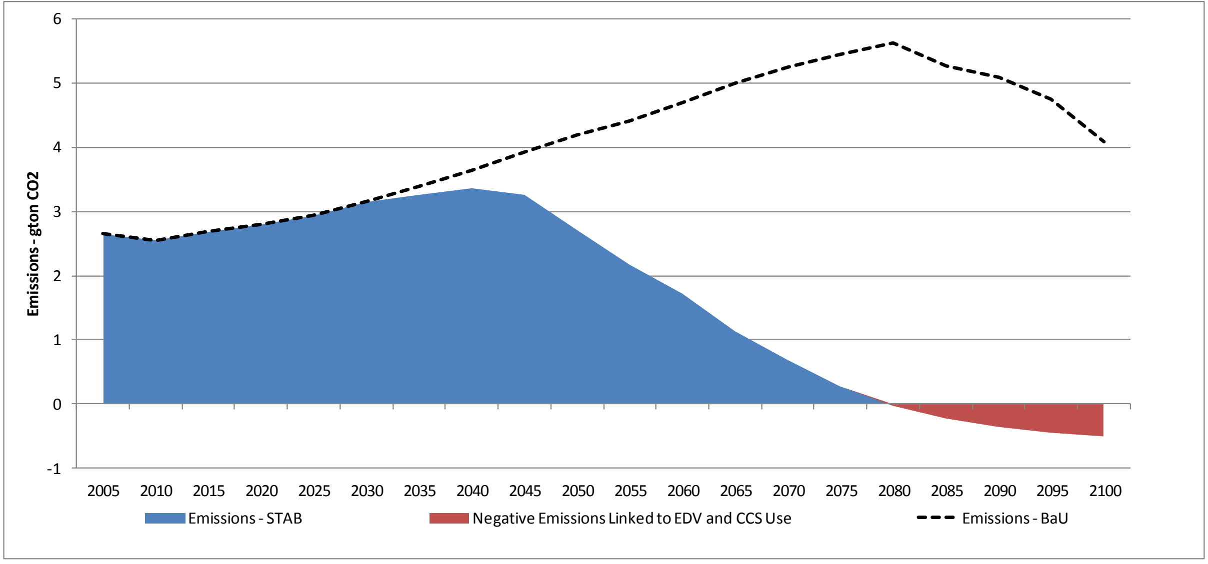


Figure 14. Global STAB Emissions and Emissions Reduction

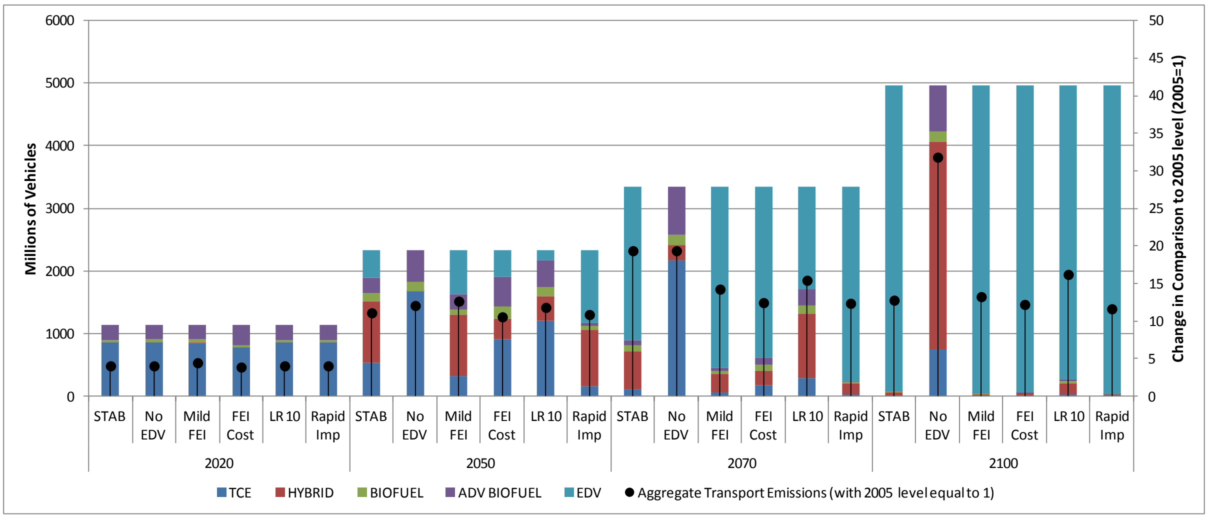


Additional Stabilisation Scenarios

As the availability of alternative technologies will play a major role in determining the feasibility and the cost of climate policy we will now review a set of alternative stabilisation scenarios which have been summarized within table 3. Noted first in table 3 is a description of the scenario reviewed in the previous section – the STAB scenario – which will be the basis of comparisons to the other scenarios. As the decarbonisation of the LDV transport sector has been identified as an important issue in achieving a cost effective climate policy target – the second scenario is the case where there is no major breakthrough in the cost and efficiency of batteries employed in EDVs and is entitled 'No EDV'. Note that innovations in batteries also do not occur in the case of traditional hybrid vehicles. The range of alternative stabilization scenarios is then extended by further investigating the model's sensitivities to the underlying FEI assumptions with the application of the 'Mild FEI' scenario. As the fuel efficiency of vehicles is a key determinant of the transport sector's impact on emissions and fuel use, a study conducted by the IEA and incorporated into the World Energy Outlook 2009 has been used to review the impacts of alternate estimates of FEI and the simultaneous incorporation of a vehicle specific cost mark-up associated with these FEIs. Named the 'FEI Cost' scenario, this scenario will allow a comparison between the Strong FEIs applied in the STAB scenario and the maximum amount of efficiency improvement which has been deemed possible by the IEA and a range of experts from around the globe. The sensitivity of the results to the assumptions used in the learning by searching endogenous technical change component are tested in LR 10 with the rate of learning being reduced from 0.20 to 0.10. The last stabilization scenario, Rapid Imp, is an endogenous scenario that matches the historical price path with a learning rate of 0.50.

Turning our focus to figure 15, we can now review the changes in the global vehicle share within the five additional stabilization scenarios in comparison to the STAB scenario. Within figure 15 the different vehicle distributions are displayed along with a comparison to the aggregate amount of emissions since 2005. While scenarios show major differences up to 2050, electrification of the LDV transport sector tends to occur in the latter part of the century in all but one of the stabilization scenarios. Hybrid drive vehicles tend to prevail as an interim technology option. The appeal of EDVs has been identified as being at least partially due to the fuel options which prevail irrespective of a higher investment cost. Amongst the six different scenarios, the No EDV scenario stands out as being quite different and this is a trend that will continue throughout the next section. As the No EDV scenario is constrained to emission reductions through fuel efficiency improvements, the use of biofuels and the introduction of traditional hybrid vehicles, the carbon price is notably higher than that for the other STAB scenarios. This coincides with higher climate policy costs, a higher World oil price and a higher overall use of oil and biomass in the World economy. Figure 15 also shows that the Mild FEI and FEI cost scenarios tend to be in line with the STAB scenario with similar trends and the electrification of the LDV transport sector tending to occur around 2045-2050. An exception to this is the lower level of diffusion of hybrids and the in-availability of advanced biofuel in the FEI cost scenario. The Rapid Imp scenario sees an earlier diffusion of hybrid and electric drive vehicles with rapid diffusion between 2025 and 2050 due to lower vehicle costs prevailing in these periods (as shown in figure 7 and titled 'World EDV Price – Exogenous – Rapid Improvement').

Figure 15. Global Vehicle Distributions in a climate constrained world: alternative transportation scenarios.

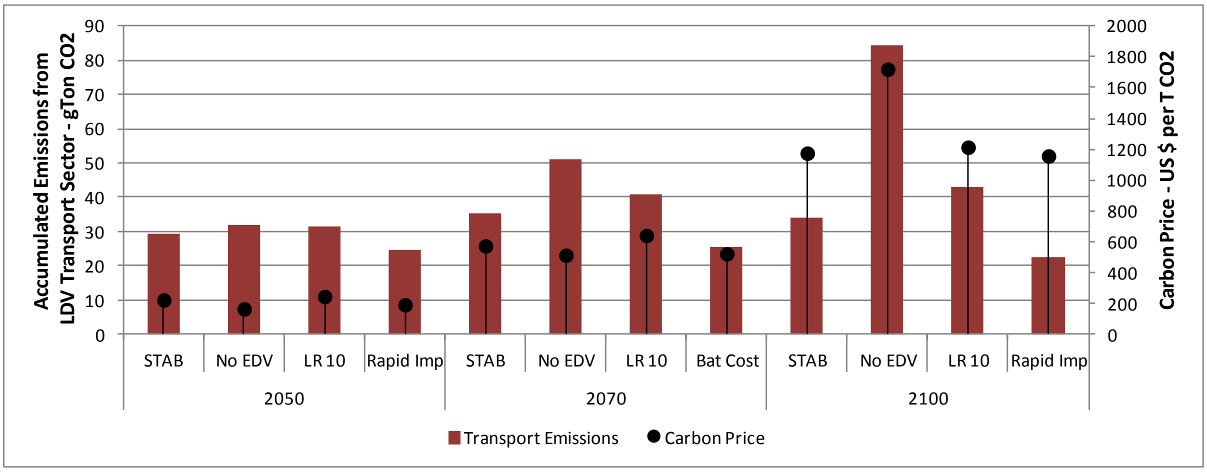


STAB: basic assumptions; No EDV: Electric Drive Vehicles never come online; Mild FEI: Fuel Efficiency follows the Mild trajectory; FEI Cost: maximum potential for FEIs based on IEA study; LR 10: Learning by searching in advanced transportation technologies is lower; Rapid Imp: more rapid diffusion of EDV applied exogenously.

The sensitivity of the model to the existence of EDVs can be explained once we consider the amount of aggregate emissions from within the LDV transport sector for each scenario and compare them to the global carbon price. Figure 16 does this by showing the sensitivity of the carbon price to higher aggregate emissions (attributed to the No EDV scenario) and the insensitivity of the carbon price to lower aggregate emissions from within the LDV transport sector (as is the case with the Rapid Imp scenario). A notable feature of the WITCH model is that the emergence of EDVs within the transportation sector is matched to both vehicle costs and the WITCH model's representation of the electricity sources within energy sector. In other words, the earlier introduction of EDVs in the STAB scenario (relative to the BaU) depends on decarbonised electricity options and without the decarbonisation of the LDV transportation sector; notable constraints are placed on the other sectors of the economy. Within the WITCH model the energy sector has had to compensate for continued reliance on fossil fuels and no decrease in the amount of travel performed or the amount of vehicles purchased. Indeed, all scenarios except for the No EDV scenario show a similar trend over time and a stabilisation of world concentrations of GHGs at 550ppm CO_2-eq at a cost of approximately US

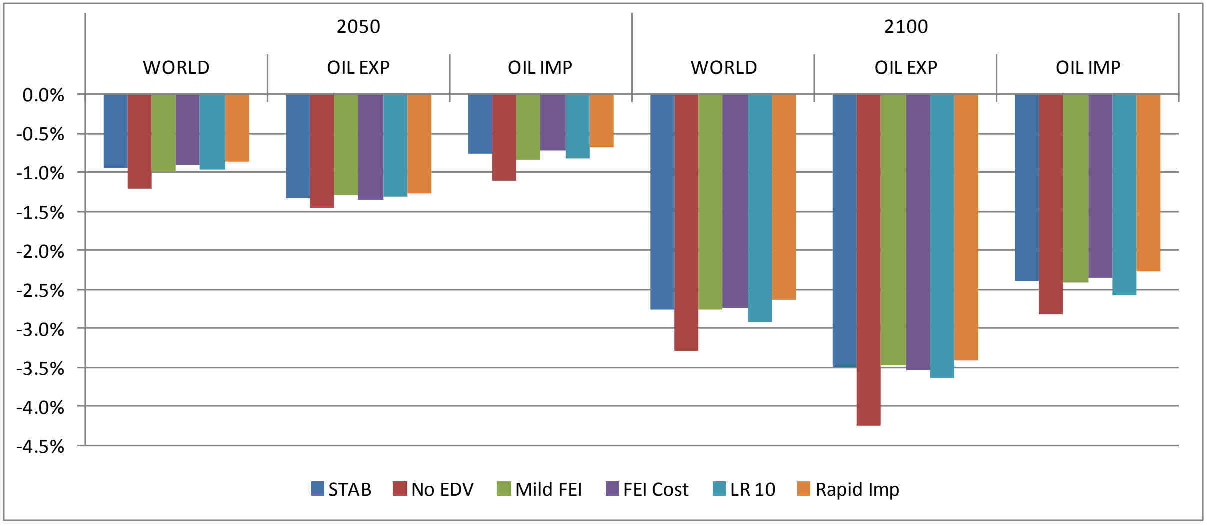
$1200 per tonne of carbon in 2100. The case of No EDVs diverges in the middle of the century, with the price of carbon increasing steadily until approximately US $1720 per tonne of carbon. This matches the trends in policy costs, shown in figure 17, where the global costs of climate policy are shown as a percentage of GDP. In 2050, the policy cost has already started to reflect the underlying trends in the economy with the No EDV scenario, the Mild FEI scenario and the LR10 scenario all having policy costs higher than the STAB. In the Mild FEI and LR10 scenarios, the higher costs in oil importing countries (OIL IMP) are primarily due to the rate of the introduction of EDVs and associated investments in R&D for battery related technologies. In the No EDV scenario, the higher cost is due to a range of factors which include sustained levels of oil use in the transport sector and pressure to utilize or develop alternative energy/fuels. In 2100, the World policy cost for all scenarios (except for the No EDV and Rapid Imp scenario) tends to be between 2.7% and 2.8% of global GDP. For the No EDV scenario the policy cost is approximately 3.3% of global GDP and this confirms that the electrification and decarbonisation of the LDV transport sector is a notable issue in achieving a cost effective climate policy. The case of higher improvements in battery costs (Rapid Imp) results in policy costs of 2.6% of global GDP and reflects the relative insensitivity of the policy cost to lower emissions from the LDV transport sector. In addition to the carbon price, the cost of having no breakthrough in EDVs also impacts the world oil price. An increase in the oil price results in a mark up of approximately 24% of the STAB scenario price in 2100. Already significant, these costs are sure to rise in the complementary case of no electrification within freight transport – a sector of interest but one not yet directly modelled within WITCH as it remains part of the non-electric sector.

Figure 16. Carbon Price in a climate constrained world: alternative transportation scenarios.



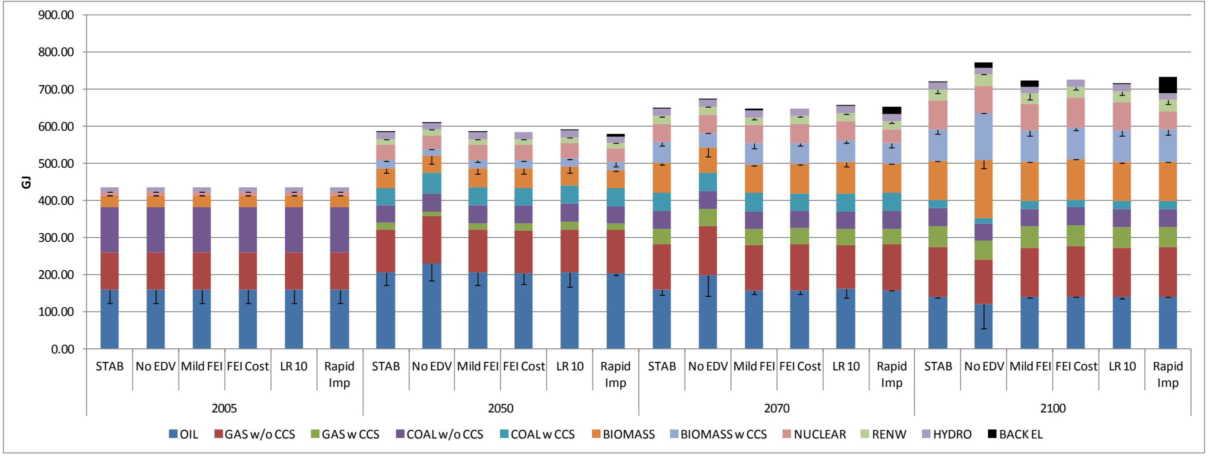
STAB: basic assumptions; No EDV: Electric Drive Vehicles never come online; Mild FEI: Fuel Efficiency follows the Mild trajectory; FEI Cost: maximum potential for FEIs based on IEA study; LR 10: Learning by searching in advanced transportation technologies is lower; Rapid Imp: more rapid diffusion of EDV.

Figure 17. Global Climate Policy Costs (% of GDP) : alternative transportation scenarios



STAB: basic assumptions; No EDV: Electric Drive Vehicles never come online; Mild FEI: Fuel Efficiency follows the Mild trajectory; FEI Cost: maximum potential for FEIs based on IEA study; LR 10: Learning by searching in advanced transportation technologies is lower; Rapid Imp: more rapid diffusion of EDV.

Figure 18. Primary Energy Supply – Global – Overall Economy Supply and Transport Sector Fuel Use



Note: The drop down lines represent the amount of transport energy use for the major fuels of interest. STAB: basic assumptions; No EDV: Electric Drive Vehicles never come online; Mild FEI: Fuel Efficiency follows the Mild trajectory; FEI Cost: maximum potential for FEIs based on IEA study; LR 10: Learning by searching in advanced transportation technologies is lower; Rapid Imp: more rapid diffusion of EDV.

Upon reviewing the total energy supply, as displayed within the figure 18, we can see that the STAB, Mild FEI, FEI Cost and LR 10 scenarios have a similar trend and level of total energy supply. The No EDV scenario leads to a case where continued oil dependence in the transport sector results in almost 55% of oil use in the global economy being used for LDV transport alone. In 2100, this corresponds with a level of oil use that is equal to 55% of the 2005 level of oil consumption, an oil price that is 54% higher than the BaU price and a carbon price 46% higher than that of the STAB scenario. The No EDV scenario and Mild FEI scenarios place pressure on the rest of the economy as reflected in the higher carbon price, policy costs and the entrance of a backstop technology in the electric sector that does not get utilised by EDVs (denoted as BACK EL in figure 18). While the introduction of BACK

EL in the Rapid Imp scenario is due to a higher use of electricity by LDV transport. As noted, it is likely that the costs of climate policy, carbon and oil would increase with the introduction of additional sectors which are also dependent upon oil – such as freight transport and air transport. Note that within the WITCH model, a non-electric oil sector represents these other sources of oil demand. At this point in time, reviews of prevailing rigid demand outside the LDV transport sector have not been explored.

While a 450 ppm GHG stabilization scenario is unlikely to be the result of climate policy negotiations in the near future, it is a target that has been deemed necessary by the IPCC to avert warming above a 2% temperature increase above pre-industrial levels. Within the WITCH model such a scenario corresponds with a temperature slightly below 2 degrees in 2100. In achieving this limited temperature increase, the model predicts the introduction of EDVs from as early as 2030. The case of 450ppm CO2 stabilization without electric drive vehicles is a scenario that is difficult to achieve without flexibility mechanisms (such as the banking and borrowing of tradable permits) and/or extreme fuel efficiency improvements above those stipulated within this paper and shown in figure 5. A 450 ppm GHG stabilization scenario would also need to account for significant advances in R&D to achieve early electrification of the LDV transport sector and this will be reviewed in future research. Electrification of other transport sectors, such as freight, will also be important.

Section 5 – Conclusion

The results in section 4 highlight that the light duty vehicles sector and policies affecting it can have major effects in the cost and feasibility of long term stabilisation policies discussed within international climate policy negotiations. As noted in the introduction, a long term effort to decarbonise the economy clearly cannot be planned without a careful analysis of long term dynamics in the transportation sector. Decarbonisation is important as it allows the fuel demand and the related travel demand of the transport sector to be matched to the advances being made in the energy sector. The results of the model show that while the relative fuel costs will assist in the penetration of alternative vehicles and the use of alternative fuels, the investment cost at the time of purchase proves quite decisive in an economic model of this type. The incorporation of income stratification would allow emerging technologies to penetrate sooner, however as a representation of the penetration of the dominant commercially successful technology this model is suitable. Irrespective of the lack of income stratification, factors such as the cost of batteries, the price of carbon and the type of fuel used are important determinants in the likelihood of commercial success for a range of alternative vehicles under a stabilisation scenario.

More specifically, the projections of GDP and population within the WITCH model imply a significant increase in the use of vehicles across the majority of regions around the globe in the medium to long term future. The emergence of China and India leads to a considerable increase in the demand for fossil fuels by the LDV transport sector in the latter half of the century. Within the business as usual scenario, LDV transport sector oil use in China and India for the year 2050 is forecast to be around 8 times the 2005 level. Meanwhile the OECD is expected to decrease their use of oil in the LDV transport sector, with 2050 levels being forecasted at 67% of 2005 levels. A climate policy commencing in 2025 and achieving stabilised world concentrations of GHGs at 550ppm CO_2-eq by 2100 tends to hasten the introduction of electric drive vehicles in all regions with electric drive vehicles entering around mid century and becoming dominate in most regions in the latter half of the century. The ability of electric drive vehicles to match the decarbonisation of the other energy intensive industry assists in keeping carbon costs down and policy costs to a minimum.

As the range of simulations shows, climate policy costs and the carbon price in the latter half of the century are sensitive to a lack of electric drive vehicles. Prevailing fossil fuel use within a no EDV scenario places notable strain on the other sections of the economy. For example, policy costs in the base stabilisation scenario tend to be 2.7% and 2.8% of global GDP, but for simulations with no electric drive vehicles, the policy cost for achieving a 550ppm GHG concentration at 2100 increases to 3.3% of global GDP. Policy costs of this magnitude confirm that the electrification and decarbonisation of the LDV transport sector is a notable issue in achieving a cost effective climate policy. In addition to the carbon price, the cost of having no breakthrough in EDVs also has a notable impact upon the world oil price. The increase in the world oil price due to the prevailing use of fossil fuels results in an oil price in 2100 that is approximately 54% higher than the price within the base stabilisation scenario. Already significant, these costs are sure to rise in the complementary case of no electrification within freight transport and the case of continued dependence of oil in fuelling air transport. Even without the modelling of these other transport sectors, what is evident is that a long term effort to decarbonise the economy must be carefully planned and take into account the rigidity that the demand for mobility is likely to produce.

And while the achievement of stabilised GHGs is a very relevant ideal, at least in the short term, voluntary initiatives and policies aiming at transforming the transportation sector are likely to take a primary role. Indeed, transport is subject to local pressures based on local pollution, congestion, regional technological and resource characteristics, which give arise to a range of policies which indirectly have an impact upon GHG emissions. An example of such policy is the legislation that a certain proportion of fuels in the USA and Europe be sourced from renewable sources, such as ethanol and other types of biofuels. The results of this model imply that the success of Renewable Fuel Standards in both the USA and Europe is likely to be contingent upon the expansion of advanced biofuels. Policy within developing countries will also need to be improved to match the increasing levels of vehicle ownership and the related rise in local pollutants. Irrespective of a steadying rate of vehicle use within OECD nations, the model’s long term projections show significant growth in the number of vehicles within the non-OECD nations from 2050 onwards.

The number of vehicles in OECD countries does increase from existing high levels and this corresponds with the OECD ‘Environmental Outlook to 2030’ which identifies transport as a key area needing address. For example, it mentions that “Transport pricing should fully reflect the costs of environmental damage and health impacts, e.g. through taxes on fuels (including the removal of tax exemptions) and road pricing”. (OECD (2008): 32) Specifically on the issue of non-OECD regions, the same report states that the “research and development of new transport technologies, including vehicles with better fuel economy, hybrid vehicles, etc., should be promoted, especially to help offset projected rapid increases in motorisation in non-OECD countries”. (OECD (2008): 32) This is a statement with which the current results from the WITCH model both confirm and further reinforce. While future work will focus on the issues of R&D investments, as well as extend the discussion on the timing and the costs of the commercial success of new transport technologies (such as advanced biofuels and EDVs), this current paper highlights the importance that such technologies have in achieving cost-effective climate policy. Privately owned transport and a continued demand for mobility do present notable issues that the climate policy discussion must examine. Key indicators such as the price of oil, policy costs and the price of carbon are sensitive to the emergence of breakthrough technologies. This is due to both the change in energy demand from within the transport sector and the additional pressure that oil-fuelled transport can place on the other sectors of the economy.

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Appendix

Table 1Aa. Key Indicators per region (2005)

	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA	INDIA
Annual Kilometres Driven (Per Vehicle)	19000	14000	11000	17000	13000	13000	13000	10000	8000	10000	10000	12000	8000
LDV total stock (millions of vehicles)	206	204	34	27	72	50	11	18	2	20	9	71	9

Table 1Ab. Key Indicators per vehicle (% Increase with respect to Traditional Cars)

Vehicle Type	TCARS	TR HYBRID	TR BIOFUEL	ADV BIOFUEL	DIESEL	D HYBRID	BIODIESEL	ADV BIODIESEL	LPG	PHEV	EDV
Cost of Purchase (% Increase)	0.0	76.2	0.0	0.0	13.2	99.4	13.2	13.2	4.7	86.4	143.2
O&M cost (% Increase)	0.0	0.3	0.0	0.0	-0.2	0.1	-0.2	-0.2	-0.3	0.7	1.5

Table 2A 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_{ldv}	Investment in LDV
$O\&M_{ldv}$	Operation and maintenance costs for LDV
$FE_{ldv,j}$	Fuel Expenditure for LDV and technology j
K_{ldv}	Stock of LDV capital
D	Depreciation rate of LDV capital stock
SC_{ldv}	Investment cost of LDV
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
$LDVpc$	Number of LDVs per capita

Table 3A LDV ownership growth rates at different income and car ownership levels

Per Capita Income Levels	Ownership growth elasticity relative to income growth (pct basis)	Maximum ownership level for this growth rate
until $5k income	0.30	no maximum
>$5k	1.30	300 cars per cap
>$5k	0.60	500 cars per cap
>$5k	0.25	600 cars per cap
>$5k	0.10	

Replication from Fulton and Eads (2004).

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