UNIVERSITY OF LEEDS

This is a repository copy of *The UK transport carbon model: An integrated life cycle approach to explore low carbon futures*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/99433/

Version: Accepted Version

Article:

Brand, C, Tran, M and Anable, J orcid.org/0000-0002-4259-1641 (2012) The UK transport carbon model: An integrated life cycle approach to explore low carbon futures. Energy Policy, 41. pp. 107-124. ISSN 0301-4215

https://doi.org/10.1016/j.enpol.2010.08.019

(c) 2010, Elsevier Ltd. This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/

Reuse
Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher’s website.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Manuscript Draft

The UK Transport Carbon Model: an integrated lifecycle approach to explore low carbon futures

Author names and affiliations:

Christian Brand[1*], Martino Tran[2] and Jillian Anable[3]

[1] Environmental Change Institute, University of Oxford, South Parks Road, Oxford, OX1 3QY. Tel: +44 (0)1865 285177; E-mail: christian.brand@ouce.ox.ac.uk [*]

[2] James Martin 21st Century School and Transport Studies Unit, University of Oxford, South Parks Road, Oxford, OX1 3QY. Tel: +44 (0)1865 295070; E-mail: martino.tran@ouce.ox.ac.uk

[3] The Centre for Transport Research, University of Aberdeen, St Mary's, Elphinstone Road, Aberdeen, Scotland, AB24 3UF. Tel: +44 (0)1224 273795. E-mail: j.anable@abdn.ac.uk

[*] Corresponding author

ABSTRACT

Current debate focuses on the need for the transport sector to contribute to more ambitious carbon emission reduction targets. In the UK, various macro-economic and energy system wide, top-down models are used to explore the potential for energy demand and carbon emissions reduction in the transport sector. These models can lack the bottom-up, sectoral detail needed to simulate the effects of integrated demand and supply-side policy strategies to reduce emissions. Bridging the gap between short-term forecasting and long-term scenario “models”, this paper introduces a newly developed strategic transport, energy, emissions and environmental impacts model, the UK Transport Carbon Model (UKTCM). The UKTCM covers the range of transport-energy-environment issues from socio-economic and policy influences on energy demand reduction through to lifecycle carbon emissions and external costs. The model is demonstrated in this paper by presenting the results of three single policies and one policy package scenario. Limitations of the model are also discussed. Developed under the auspices of the UK Energy Research Centre (UKERC) the UKTCM can be used to develop transport policy scenarios that explore the full range of technological, fiscal, regulatory and behavioural change policy interventions to meet UK climate change and energy security goals.

Keywords: Transport energy modelling, Transport carbon emissions; Strategic policy analysis; Scenario development

1 INTRODUCTION

Ambitious targets for greenhouse gas (GHG) reductions and concerns about energy security require comprehensive policy strategies to achieve those goals. These strategies are likely to involve a multitude of policy measures that will need to be integrated and carefully timed. This is particularly so in the transport sector, which is perceived as the most difficult sector to decarbonise and where there is a growing consensus that we will not achieve a low carbon transport system without a combination of demand management, operational, pricing and technical policy options (CfIT, 2007; Hickman and Banister, 2007). Policy makers often struggle with developing comprehensive strategies aiming to achieve a low carbon transport system, reverting to mostly technological options and assuming that society and preferences will not change. In the UK, for example, national strategy development within central government is mostly informed by techno-economic modelling of the energy system (e.g. using MARKAL, Loulou et al., 2004) and/or the transport system (e.g. using the National Transport Model, DfT, 2005). While these models are good at exploring the near to medium term future based on incremental change and technological evolution, they are not particularly good at modelling the wider set of demand and supply-side policies within a changing society and economy. This paper addresses some of these methodological gaps in scenario modelling by introducing a newly developed strategic transport-energy-environment model called the UK Transport Carbon Model (UKTCM).

Developed under the auspices of the Energy Demand theme of the UK Energy Research Centre (UKERC), the UKTCM is a highly disaggregated, bottom-up model of transport energy use and life cycle carbon emissions in the UK. In a nutshell, the UKTCM provides annual projections of transport supply and demand, for all passenger and freight modes of transport, and calculates the corresponding energy use, life cycle emissions and environmental impacts year-by-year up to 2050. It takes a holistic view of the transport system, built around a set of exogenous scenarios of socio-economic and political developments. The model is technology rich and, in its current version, provides projections of how different technologies evolve over time for more than 600 vehicle technology categories[1], including a wide range of alternative-fuelled vehicles such as more efficient gasoline cars, hybrid electric cars, plug-in hybrid vans, battery electric buses and advanced aircraft. However, the UKTCM is specifically designed to develop future scenarios to explore the full range and potential of not only technological, but fiscal, regulatory and behavioural change transport policy interventions. An example is the recent Energy2050 work of the UK Energy Research Centre where UKTCM played a key role in developing the 'Lifestyle' scenarios (Anable et al., forthcoming; UK Energy Research Centre, 2009).

The paper proceeds as follows: first, a short review presents the context in which the UKTCM has been developed, focusing on carbon reduction analysis and the presence (or lack) of similar strategic models; second, an overview of the modelling approach

---

[1] A UKTCM 'vehicle technology' is defined as a typical representative of a combination of transport type (passenger or freight), vehicle type (e.g. motorcycle, car, HGV, train, aircraft), vehicle size (e.g. small car, van, heavy truck, intercity rail, medium sized aircraft for short haul European), fuel type (e.g. gasoline, diesel, E85, electricity), 'vintage' (e.g. ICV Euro IV 2005-09, ICV "Euro VIII" 2020-24, fuel cell EV Standard 3) and hybridisation (ICV, HEV, PHEV). 'Vintage' is used to simulate changes in performance, preferences and cost over time. Table 3 below lists the technologies currently implemented.

and methods used is given, including more detail on a couple of key features; third, the model is demonstrated by presenting the results of a reference scenario for the UK transport system up to 2050, followed by the comparison of three alternative single policy scenarios and a policy package; fourth, the limitations of the model are discussed before concluding with a summary of the results, ongoing parallel work and an outlook for future work. For more detail on the modelling methods and data assumptions see the UKTCM Reference Guide v1 (Brand, 2010a). For details on the user interface see the UKTCM User Guide v1 (Brand, 2010b). Both are available to download from the UKERC website (www.ukerc.ac.uk).

2 BACKGROUND

2.1 Carbon pathways

At the global level, transport currently accounts for nearly 25% of energy related carbon dioxide (CO_2) emissions (IEA, 2008). From a 2005 baseline, energy use and related CO_2 emissions are expected to increase by more than 50% by 2030 and more than double by 2050 (ibid.). The fastest growth in emissions will likely arise from light-duty vehicles (i.e. passenger cars, small vans, sport utility vehicles), air travel, and road freight (ibid.). In the UK, although economy wide emissions reduction of 18% were achieved since 1990, domestic transport emissions increased 11% from over the same period reaching 135 Million tonnes of CO_2 ($MtCO_2$) in 2007 comprising 24% of total UK domestic emissions (CCC, 2009). The largest share of UK transport emissions is from road passenger cars at 86% followed by buses at 4%, rail at 2%, and domestic aviation at 2%. Importantly, this does not include an estimated 38 $MtCO_2$ from international aviation which if accounted for would increase the contribution of transport to total UK emissions (CCC, 2009; Jackson et al., 2009). Therefore, without significant contribution from the transport sector, the target recommended by the UK Committee on Climate Change (CCC) to cut CO_2 equivalent of Kyoto GHGs emissions by 80% between 1990 and 2050 will not likely be achieved.

Transport is invariably deemed to be the most difficult and expensive sector in which to considerably reduce energy demand and greenhouse gas emissions (Enkvist et al., 2007; HM Treasury, 2006; IPCC, 2007). The analysis on which such conclusions are based tends to rely on forecasting and modelling frameworks which accentuate technical solutions and economically optimal and rational behaviour of individual consumers and markets, often based on historic consumer preferences. More often than not, the transport policy response to this issue reflects this dominant techno-economic analytical approach and focuses on supply-side vehicle technology efficiency gains and fuel switching as the central mitigation pathway for the sector.

What is under-researched (with the notable exception of DfT, 2008a) and sometimes even overlooked is timing – the rate of progress in reducing carbon is as important as the end target date. Given the longevity of CO_2 in the atmosphere (Inman, 2008), what really counts in terms of mitigating climate change is a reduction in cumulative emissions. While late action will make it much harder to achieve carbon targets based on cumulative emissions, early action on the ‘low hanging fruit’ (e.g. speed limit enforcement, fuel duty increases) will make it easier in the long term.

2.2 Strategic modelling of the transport-energy-environment system

For strategic modelling of the transport-energy-environment (TEE) system, essentially three different approaches have been pursued in Europe (for an overview see e.g. Burgess et al., 2005), involving (1) top-down equilibrium or optimisation models such as PRIMES (Syri et al., 2001) and MoMo (Fulton et al., 2009); (2) bottom-up simulation models such as TRENDS (Georgakaki et al., 2005), TREMOVE (De Ceuster et al., 2004), Zachariadis (2005) and Schäfer and Jacoby (2006); and (3) transport network models such as ASTRA (Martino and Schade, 2000), SCENES (IWW et al., 2000) and EXPEDITE (de Jong et al., 2004). The majority of these models were designed to explore specific policy questions, focusing on economic and technology policy interventions and their effects on transport demand, with some modelling of (direct) energy use and emissions. They often lack the detail necessary to model national low carbon policies that go beyond techno-economic policy options, e.g. policy aimed at changing travel behaviour. Models based solely on econometric approaches are deemed to be inappropriate for looking into the medium to long term future, as societies, preferences and habits (and thus elasticities) change.

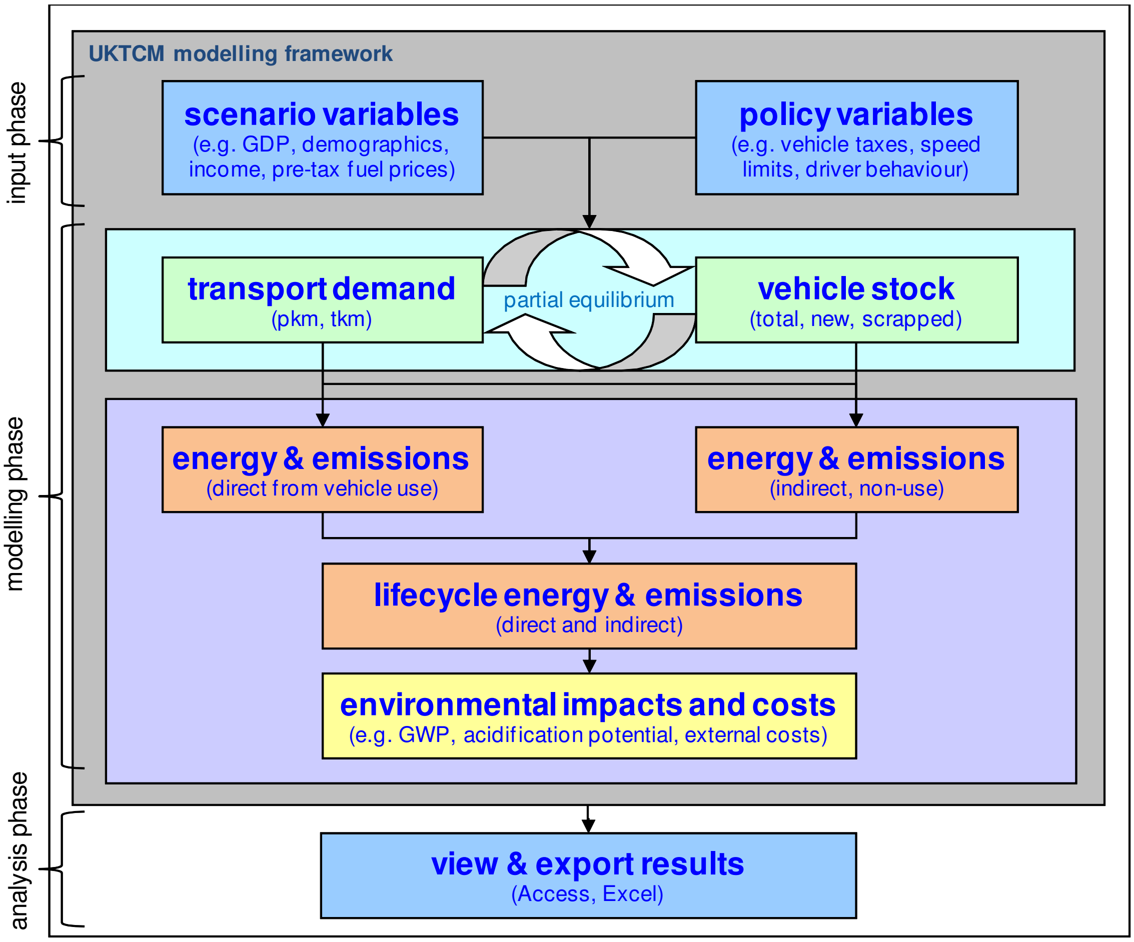
At the national level a number of models exist, see e.g. de Jong et al. (2004). In the UK, no truly integrated TEE model exists at present, and policy makers rely on running different sets of models such as the (road) National Transport Model (NTM; DfT, 2005), with separate models for rail, aviation and navigation. In addition, transport and climate mitigation policy is informed by energy and economy systems modes such as MARKAL (Loulou et al., 2004), seeking to explore intra-sector dynamics and trade-offs. Although the models cover the majority of GHG emissions sources and types, they do not project full life cycle emissions. Finally, and crucially for the research community, assumptions and methods of government run models are often not explicit, making independent scenario planning and policy analysis difficult. The lack of an integrated policy-relevant life cycle model of carbon emissions from transport was the main motivation for the development of the UKTCM, which is described next.

3 MODEL DESIGN AND METHODS

3.1 Model overview and architecture

The UKTCM is designed around (a) a set of quantified scenarios which describe a range of possible external political and socioeconomic developments envisaged up to 2050; (b) a set of single policy options and multiple policy packages that include fiscal, technical, regulatory and demand management measures; (c) four linked models of the transport-energy-environment system; and (d) a graphical user interface, to set up and run the model and view key modelling results. Figure 1 provides an overview of the system components.

Figure 1: Components of the UK Transport Carbon Model



The set of alternative scenarios describes a range of possible external political and socio-economic developments envisaged to 2050. These ‘futures’ are quantitatively specified by a set of exogenous variables which may affect the outcomes of the models, while being outside the control of the transport-energy-environment system. These variables include changes in national GDP, pre-tax energy prices, demographics, household disposable income and maximum car ownership levels. The purpose of the scenarios is to provide a series of contexts within which the UK transport system may develop over time so that alternative policies can be tested for robustness against the uncertainties in the political, socio-economic and technological spheres.

The policy options include fiscal measures such as vehicles and fuel taxes, regulatory measures such as fuel economy standards, information and education policies and investment and planning policies. Table 1 provides a list of the main policy options that can be modelled in UKTCM, and their primary and secondary effects. Importantly, policy packages of two or more policies listed in the Table can be modelled at the same time in an integrated and internally consistent manner.

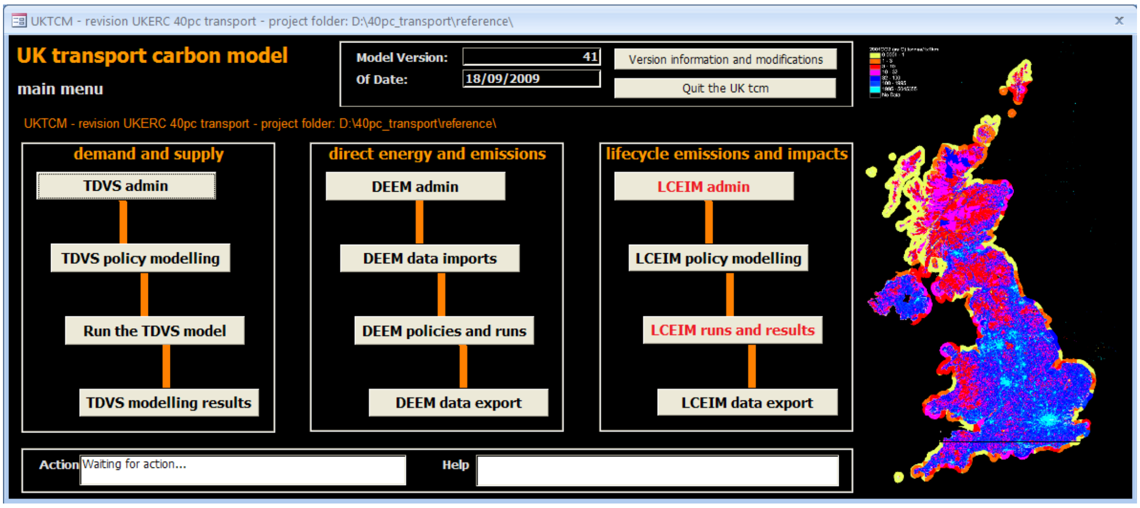
Table 1: List of the main policy options that can be modelled in UKTCM, and their effects

Policy	**Primary (and secondary) effects**	**Model**
Fiscal		
Company car tax	fleet car technology choice, (demand)	VSM/TDM
Vehicle circulation tax	road vehicle technology choice, (demand)	VSM/TDM
Vehicle purchase tax / feebates	vehicle technology choice, (demand)	VSM/TDM
Car scrappage incentive/rebate	private car technology choice, car ownership, (demand)	VSM/TDM
Fuel taxation (by volume or carbon content)	vehicle technology choice, (demand)	VSM/TDM
Road user/congestion charging (graduated)	vehicle technology choice, (demand)	VSM/TDM
Parking charges	vehicle technology choice, (demand)	VSM/TDM
Regulation		
Fuel economy standards (voluntary, compulsory)	vintaging of new vehicle fleets, (demand)	VSM/TDM
Regulation for low rolling resistance tyres and tyre pressure monitoring	vehicle emissions factors	DEEM
Speed limits and enforcement	road vehicle speed profiles and emissions factors	DEEM
Fuel obligations (e.g. Renewable Transport Fuel Obligation)	carbon content of blended fuel, vehicle emissions factors	DEEM
Low emission zones (carbon)	‘redistribution’ of traffic to low emissions vehicles in access areas (e.g. urban)	VSM
High occupancy vehicle lanes	average load factors, (average speeds and emissions)	VSM, (DEEM)
Information, education, smart/soft measures		
Travel plans (individualised, residential, workplace, schools)	travel activity, modal shift, average distance travelled by car	Scenario
Eco-driving / driver behaviour	vehicle emissions factors	DEEM
Labelling	technology choice (via preference parameter)	VSM
Car sharing / pooling	load factors, car demand	VSM/TDM
Planning and investment		
Parking space availability	car ownership (second, third+ car)	VSM/TDM
Rail electrification	direct emissions, indirect emissions (electricity generation)	
Changes in electricity generation	indirect emissions from (plug-in, battery) electric vehicle use	LCEIM
Additional public transport infrastructure, e.g. high speed rail investment	indirect emissions from manufacture, (modal shift, induced demand)	LCEIM, (Scenario)

Note: TDM = transport demand model, VSM = vehicle stock model, DEEM = direct energy use and emissions model, LCEIM = life cycle and environmental impacts model

The user accesses the model mainly via a newly developed graphical user interface which serves as the main portal for setting up the exogenous scenarios, endogenous policies and policy packages, running of the modelling chain, visualisation of the results in tabular and graphical form, and semi-automated export to Excel or similar analysis software packages (Figure 2). It has been developed in Microsoft Access 2007 as a relational database system.

Figure 2: Screenshot of the main menu of the UKTCM user interface



UKTCM - revision UKERC 40pc transport - project folder: D:\40pc_transport\reference\

Model Version: 41

Of Date: 18/09/2009

Action: Waiting for action...

Help:

The four linked models represent the core of the modelling system and describe the transport system and calculate their impacts. They are: the transport demand model (TDM), the vehicle stock model (VSM), the direct energy use and emissions model (DEEM) and the life cycle and environmental impacts model (LCEIM). The following Sections describe the four linked models in more detail with particular focus on how UKTCM models vehicle ownership, technology choice and life cycle emissions.

3.2 Transport demand model

Approach

The TDM is a simple demand model using a two-pronged approach. For each of the main modes of transport, demand is either (a) calculated endogenously year by year up to 2050 employing a typical econometric demand model or (b) simulated with exogenous assumptions on how travel activity, modal split and trip distances may evolve over time.

In ‘forecasting mode’ (simple econometric model), the evolution of demand depends on exogenous scenario parameters such as GDP, the number of households and the population’s propensity to travel. It is also affected by the evolution of energy prices and changes in the relative average ownership and operating costs for each transport demand segment (Table 2), dependent on the mix of vehicle technologies in the vehicle fleet and their underlying costs, via a feedback loop from the VSM (see Equation E1 below). This allows exploring slightly more radical changes in consumer preferences and system changes that are not easy to model using standard econometric techniques based on historic consumer preferences (revealed through elasticities of demand). This two-pronged approach aims to provide a set of plausible developments of transport demand – it is not intended to provide an accurate prediction of the most likely future development of transport demand. In ‘simulation mode’, demand is decoupled from forecasting in that the user puts in an externally derived or otherwise published demand projection. Simulation mode can be used to define alternative scenarios based on more detailed changes in travel patterns by trip purpose, trip lengths and frequency.[2] For example, this has been done for alternative scenarios on lifestyle changes as part of the UKERC Energy2050 project (UKERC, 2009).

The final outputs of the demand model are passenger transport demand (expressed in passenger-kilometres, or pkm) and freight transport demand (expressed in tonne-kilometres, or tkm) for the demand segments summarised in Table 2.

---

[2] Currently the task of defining alternative demand projections is performed ‘off model’ in a detailed spreadsheet that depicts travel patterns in terms of trip purpose, frequency and lengths. As part of UKERC work it is planned to incorporate and formalise this into the next version of UKTCM.

Table 2: The UKTCM transport demand segments

Passenger demand segments		**Freight demand segments**	
Mode	**Journey segment**	**Mode**	**Journey segment**
Walking	Urban	LDV (vans)	Urban
Cycling	Urban / non-urban		Rural
Motorcycle	Urban		Motorway
	Rural	HGV (trucks)	Urban
	Motorway		Rural
Car	Urban		Motorway
	Rural	Rail	Dedicated rail freight
	Motorway	Navigation	Inland / domestic
Bus	Local bus (urban)		Coastal / domestic
	Coach (motorway)		Maritime / intern.
	Minibus (rural)	Air freight	Domestic short haul
Rail	Light rail and underground		International medium haul / Europe
	Regional rail		International long haul / intercontinental
	Intercity rail		International supersonic
	High speed rail		
Passenger air	Domestic short haul		
	International medium haul / Europe		
	International long haul / intercontinental		
	International supersonic		

Overview of model specification

Demand is derived as an econometric function of exogenous parameters, together with their respective elasticities of demand. Separate demand functions are used for each mode of transport as listed in Table 2, taking on the form shown in Equation E1:

$$\left[\frac{T_n}{T_{n-1}}\right]=\left[\frac{GDP_n}{GDP_{n-1}}\right]^{EGDP}*\left[\frac{NHH_n}{NHH_{n-1}}\right]^{ENHH}*\left[\frac{RC_n}{RC_{n-1}}\right]^{-ERC} \qquad \text{(E1)}$$

where T = demand for travel (expressed in passenger-km and tonne-km)
GDP = Gross Domestic Product
NHH = total number of households
RC = relative vehicle ownership and operating costs for a demand segment
Exx = elasticity with respect to xx
n = modelling year (currently 1996, 1997, …, 2050)

The relative ownership and operating costs RC_n for each demand segment are the relative changes from year n-1 to year n of the average weighted costs fed back from the VSM. The VSM calculates ownership and operating costs for each vehicle technology based on a number of cost categories, including the average pre-tax purchase price (NB: price, not engineering cost), any purchase taxes or incentives (e.g. scrappage incentive), fixed operating costs (maintenance, insurance, excise duty, fixed road user charge, depreciation, etc.) and variable operating costs (fuel costs, road user charging per km or cordon entry, etc.). These are then weighted by vehicle-km and averaged over all technologies within a demand segment in year n to give a cost per passenger/tonne-km for each demand segment.

In the short run, changes in incomes and prices influence the decision of making a trip and also the decision concerning which transport mode is used (e.g. in the short run, a car has already been purchased and only the variable costs of a trip are decisive). In the long-run, changes in income and in prices can also lead to a lasting change in people’s behaviour and can influence vehicle purchase decisions (for a good review see Goodwin et al., 2004). This difference between short-run and long-run effects has been taken into account in an indirect way in UKTCM. The first two elasticities in Equation E1 reflect the short-run effects of changes in incomes and population levels on transport demand. The third elasticity simulates any additional long-run effects of relative changes of vehicle ownership and operating costs on overall demand and modal shift. Modal shift happens when the costs of providing one pkm or tkm for competing modes (say, car vs. bus vs. rail vs. air) as fed back by the VSM change relative to each other. There is an overall change in demand and also a shift from one mode to the other. The model applies default price elasticities (e.g. -0.38 for total passenger transport demand, -0.54 for cars, -0.61 for vans and trucks) to changes in vehicle ownership and operating costs RC for each mode of transport. For example, an increase in fuel duty that is only applied to cars and motorcycles, but not buses, rail and air, will result in an increase in RC for cars relative to the reference scenario as well as relative to the other modes, ultimately leading to a decrease in overall passenger transport demand and a shift towards bus, rail and domestic air. This is demonstrated below in Section 4.

To avoid a simple static approach the elasticities can take different values for each future year up to 2050. This dynamic approach allows modelling change in behaviour and preferences and avoids a simple projection of the past into the future. The estimation of the parameters for the calculation of future demand is based on statistical data for previous years and on transport demand forecasts taken from other studies. This allows the researcher and user to specify a ‘base case’ or ‘reference’ scenario against which alternative scenarios are compared.

Demand model calibration

The demand elasticities were calibrated for the base year (1995) and subsequent years up to 2007, based on published statistics of transport (DfT, 2008c), demographic (ONS, 2008) and economic (HM Treasury, 2008) data. For future years up to 2050, the elasticities were either set to historic averages (‘forecasting mode’) or derived once the user had specified an exogenous set of demand projections (‘simulation mode’).

Thus in ‘simulation mode’ internal consistency checks can be carried out by comparing the elasticities implicit in the exogenous demand, GDP and population projections with published figures. For instance, Wohlgemuth (1997) provides short-run income elasticities of demand of between 0.23 (Europe) and 0.78 (US) for distance travelled by cars, 0.39 (Europe) for tonne-km by trucks and between 1.35 (Europe) and 1.75 (US) for passenger air miles travelled. These are comparable with other studies such as Goodwin et al. (2004). Assuming a long term GDP growth rate of just 2% per year, Government projections of population growth and taking current demand projections based on DfT (2008a), the UKTCM demand model calibration implied short term (2010-2020) elasticities in the range between 0.3 and 0.4 for distance travelled by car, between 0.7 and 0.8 for tonne-km by trucks and between 1.3 and 1.6 for passenger air miles – a reasonable fit with published data (Clements, 2008; see e.g. Goodwin et al., 2004; Wohlgemuth, 1997).

3.3 Vehicle stock model (VSM)

Approach

The VSM is a disaggregate vehicle stock model that provides two key functions within UKTCM. First, it provides an evolution of the number of vehicles (total, new and scrapped) for each modelling year, disaggregated by vehicle type, vehicle size, fuel type, engine technology, vintage and age (Tables 3a and 3b provide a summary of this disaggregation). Secondly, it provides vehicle distances travelled disaggregated by vehicle size, technology and age, as input to the DEEM and the LCEIM. A crucial attribute of the stock model is that the user can test the effects of policy levers on the deployment of different technologies within the vehicle population.

Table 3a: Summary of UKTCM vehicle technologies for passenger transport

Vehicle type	**Size**	**Primary fuel**	**Engines/ drivetrains**	**No. of vintages**
Car	Small	Gasoline	ICV, PHEV	21
		Diesel	ICV	10
		Electric	Battery EV	3
		H_2, biomethanol	FC	4
	Medium	Gasoline	ICV, HEV, PHEV	30
		Diesel	ICV, HEV	21
		Biodiesel (B100)	ICV	3
		Bioethanol (E85)	ICV	9
		LPG, CNG	ICV	12
		H_2, biomethanol	FC	6
	Large	Gasoline	ICV, HEV, PHEV	30
		Diesel	ICV, HEV	22
		Biodiesel (B100)	ICV	3
		Bioethanol (E85)	ICV	9
		LPG	ICV	11
		H_2, biomethanol	FC, ICV	11
Motorcycle	Average	Gasoline	ICV	3
		Electric	Battery EV	3
		H_2	FC	3
Bus	Mini	Gasoline	ICV	3
		Diesel	ICV, HEV	22
		LPG, CNG	ICV	6
		E85	ICV	9
		Biodiesel (B100)	ICV	3
		H_2	FC	1
	Urban	Diesel	ICV, HEV, PHEV	30
		Electric	Battery EV	3
		LPG, CNG	ICV	5
		E85	ICV	3
		Biodiesel (B100)	ICV	3
		H_2, biomethanol	FC	9
	Coach	Diesel	ICV, HEV	22
		Electric	Battery EV	3
		LPG, CNG	ICV	5
		Biodiesel (B100)	ICV	3
		H_2, biomethanol	FC	9
Rail	Light, metro	Grid electricity	Electric	6
	Regional	Diesel	ICV	3
		Grid electricity	Electric	3
	Intercity	Diesel	ICV	3
		Grid electricity	Electric	3
	High speed	Grid electricity	Electric	3
Air	General aviation	Jet A-1	Turboprop	1
	Short haul, dom.	Jet A-1, H_2	Turbine	9
	Medium haul, int.	Jet A-1, H_2	Turbine	9
	Long haul, int.	Jet A-1, H_2	Turbine	9
	Supersonic, int.	Jet A-1, H_2	Turbine	9

Table 3b: Summary of UKTCM vehicle technologies for freight transport

Vehicle type	**Size**	**Fuels**	**Engines/ drivetrains**	**No. of vintages**
Trucks	Light (vans, <7.5t GVW)	Gasoline	ICV	13
		Diesel	ICV, HEV, PHEV	30
		Battery electric	Electric	3
		Biodiesel (B100)	ICV	9
		Bioethanol (E85)	ICV	9
		LPG, CNG	ICV	6
		H_2	FC	3
	Medium (7.5t - 16t GVW)	Diesel	ICV, HEV	14
		Biodiesel (B100)	ICV	4
		H_2, biomethanol	FC, ICV	14
	Large (>16t GVW)	Diesel	ICV, HEV	15
		Biodiesel (B100)	ICV	4
		H_2, biomethanol	FC, ICV	14
Rail	Regional	Diesel	ICV	3
		Grid electricity	Electric	3
Shipping	Inland	Diesel	ICV	2
	Coastal	Diesel	ICV	2
	Maritime	Diesel	ICV	2
Air	Short haul, dom.	Jet A-1, H_2	Turbine	9
	Medium haul, int.	Jet A-1, H_2	Turbine	9
	Long haul, int.	Jet A-1, H_2	Turbine	9
	Supersonic, int.	Jet A-1, H_2	Turbine	8

Where: GVW=gross vehicle weight, ICV=internal combustion engine vehicle, HEV=hybrid electric vehicle, PHEV=plug-in hybrid electric vehicle, H2=hydrogen (gaseous or liquid), B100=100% biodiesel, E85=85% bioethanol-15% gasoline blend, LPG=liquefied petroleum gas, CNG=compressed natural gas, dom.=domestic, int.=international, Jet A-1=aviation jet fuel (kerosene)

In each year the structure of the vehicle population will change due to a combination of two processes: the purchase of new vehicles and the scrapping of old ones. The process is iterative, with changes year-on-year against the vehicle population distribution for the base year. New technologies will enter the population through the purchase of new vehicles (or the upgrading of existing vehicles, e.g. trucks). For all vehicle types there is a common equation which describes the way the vehicle stock evolves over time:

$$NewVehicles(y) = TotalVehicles(y) - TotalVehicles(y-1) + ScrappedVehicles\ (y-1) \quad (E2)$$

where: y = modelling year, from (base year + 1) to end of modelling horizon

Within the VSM, the calculation of the total number of different vehicle types in the stock each year is treated separately, as different forces are assumed to affect the entry of new vehicles into the stock. The exogenous scenarios, which describe the societal factors and attitudes that partly determine vehicle ownership, affect the overall vehicle numbers and technology choice in each year. The vehicle types modelled are motorcycles, three passenger car sizes, urban buses, express coaches, mini buses, vans, medium and large trucks, four aircraft sizes, four train sizes and three shipping vessel sizes. The VSM is divided into five main stages:

1. Module to calculate car ownership, drawn upon previous household car ownership models following the development of the 1997 UK National Road Traffic Forecast model (DETR, 1997) and its improvements as specified by ITS Leeds (2001) and Whelan (2007). The module treats household ownership of a first, second and third or more car separately and draws on a number of explanatory variables such as changes in average new car prices, car ownership saturation levels, household location (urban, non-urban), household disposable income and availability of public transport;
2. For all other vehicle types a module to calculate the number of total vehicles required to fulfil demand, taking into account exogenous variables such as GDP (for road freight) and scenario variables such as average vehicle load factors;

3. A module to calculate vehicle scrappage, simulated through the modified Weibull function previously used in the FOREMOVE model (Zachariadis et al., 1995);
4. A vehicle technology choice module, based on price and non-price factors underlying purchasing decisions. New cars are further modelled by size and market segment (private, fleet/company);
5. Calculation and disaggregation of vehicle-kilometres by size, fuel type, engine technology and age, based on the demand segments derived in the TDM, vehicle load factors[3] and the highly disaggregate vehicle stock derived in steps 1-4 above.

To populate and calibrate the stock model we used a number of sources, including car ownership data (Whelan, 2007), vehicle licensing (new, total) and vehicle age distributions (DfT, 2009b), vehicle purchase prices and O&M costs (Lane, 2006; SMMT, 2009), demographic (ONS, 2008) and macro-economic data (HM Treasury, 2008).

The detailed specification of the entire VSM goes beyond the scope of this paper. However, since vehicle technology choice is an important new feature of the model it is described next.

---

[3] The 'average load factor' (in % of capacity) is an important scenario input variable for the VSM. It can be modified for the modelling years using the scenario variable 'Scen_LoadFactor', which is disaggregated by vehicle type e.g. 'vans' and route segment type e.g. 'urban' or 'motorway'.

Model specification: focus on vehicle technology choice

The purpose of the technology choice module is to split the total annual demand for new vehicles (i.e. NewVehicles(y) in Equation E2) among the different available technologies, for any specific vehicle type (such as light goods vehicles or medium-sized cars). The idea behind the model is that a vehicle of technology i is chosen with probability ($prob_i$) which is related to cost and non-cost factors of the vehicle with that technology. Cost factors are simulated by calculating the equivalent annual cost EAC_i for each technology i. Non-cost factors are simulated by a preference and performance parameter, P_i, which is an aggregate function of perceived performance (perf), market presence (pres) and consumer preference (pref) of the vehicle technology. From the mathematical point of view, the probability is modelled as a linear function of the preference and performance parameter and a logit probability function (commonly used in behavioural modelling, see e.g. Train, 2009) of the cost factors:

$$prob_i = \frac{P_i \times \exp\left(-c \times \frac{EAC_i}{\min(EAC_i)}\right)}{\sum_{j=1}^{m} P_j \times \exp\left(-c \times \frac{EAC_j}{\min(EAC_j)}\right)} \qquad \text{(E3a),}$$

with

$$P_i = perf_i \times pres_i \times pref_i \qquad \text{(E3b),}$$

where P_i = preference and performance parameter for vehicle technology i

EAC_i = equivalent annual cost of vehicle technology i

c = modelling constant (calibrated)

m = number of vehicle technologies available in modelling year

$perf_i$ = perceived performance of vehicle technology i

$pres_i$ = market presence at maturity of vehicle technology i

$pref_i$ = consumer preference for vehicle technology i

The equivalent annual cost EAC_i is the cost per year of owning and operating a vehicle over its entire (economic) lifespan. It is the sum of the annuity of owning the vehicle over its lifetime and any annual operating and maintenance costs (e.g. fuel, road user charging, circulation taxes, insurance, maintenance and depreciation) to the consumer. The annuity represents the annual payment of paying off a loan for all up-front costs (purchase price, purchase taxes and rebates). The applied discount rate can vary by vehicle type (car, van, aircraft, etc.) and, to avoid a purely static approach, by year.

For cars, the discount rate can vary by vehicle ownership type in order to simulate the differences in financial considerations and investment risk for the private (higher private rates) and fleet/company (commercial rates) car markets. The default discount rate for the private car market is 30%, simulating higher cost of capital, risk aversion and the relative importance of up-front costs in the decision making process of the private consumer. In contrast, the default discount rate for the fleet/company car market is 10%, simulating lower cost of capital and investment risk.

The P factor is an aggregate of three key factors that can influence purchasing decisions, based on market research by the UK Energy Saving Trust (2008). First, the factor of perceived performance $perf$ is an aggregate of perceived safety and security, speed, acceleration, range between refuelling, space available and comfort. Secondly, the market presence factor $pres$ represents the potential market presence of the vehicle technology at market maturity, including factors such as availability of and access to fuel as well as market coverage (i.e. is the technology widely available across the different market segments such as ‘super mini’, ‘small family’, executive’ and ‘multi-purpose vehicles’?). Thirdly, the consumer preference factor pref simulates non-cost factors that cannot be explained by cost, performance and market factors, e.g. vehicle colour, style and ‘technology loyalty’.

The obvious challenge of defining P has been approached in two different ways. First, in the case where the vehicle technology is an established one, with a consolidated market share such as gasoline and diesel cars, P can be derived using equation E3 on the basis of observed, historical data such as the UK’s Vehicle Licensing Statistics (DfT, 2009b). Since the values of P are not constant, but could change over time, it is necessary to verify their trends on the basis of observed data. In UKTCM, this verification process was performed for the base year and subsequent modelling years where licensing statistics exist (from 1995 to 2007). For example, the share of new diesel cars has increased significantly from around 20% in the late 1990s to around 50% in 2008 (SMMT, 2009). As the cost difference between gasoline and diesel cars has not changed dramatically, this trend implies that over this time period the non-cost factors for diesel cars increased relative to gasoline cars, indicating a relative improvement in performance (higher power, better acceleration, lower specific emissions), preference (decrease in perception of diesel being a dirty technology) and market potential (emergence of small diesel cars, technology availability now similar to gasoline technology).

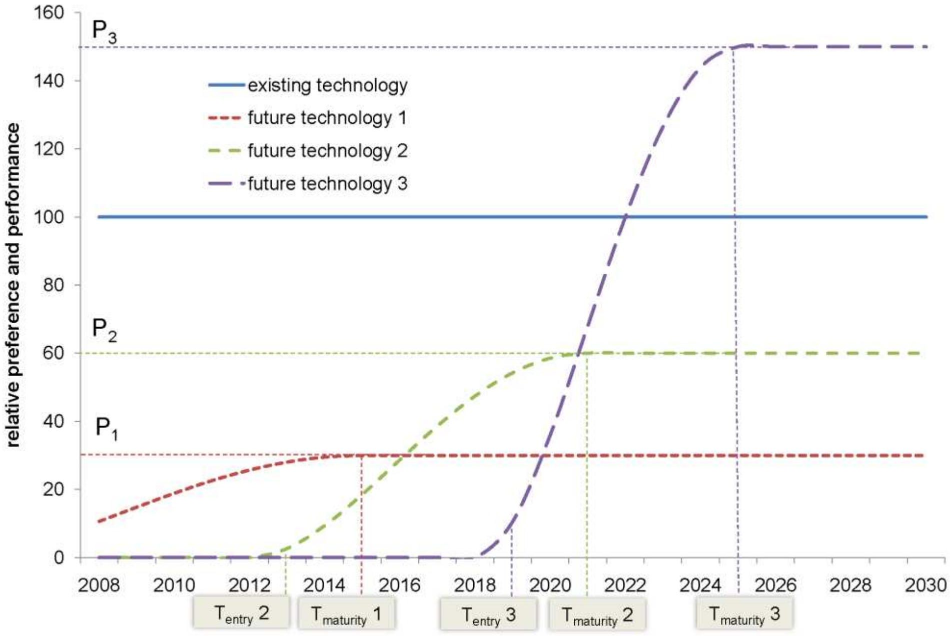
Secondly, for new and alternative vehicle technologies, neither cost nor preference and performance data are well established or can be observed directly. In addition, both cost and non-cost factors may change more radically in future years than for their conventional counterparts. Costs may decrease as production achieves economies of scale, technological developments cut intrinsic costs and vehicle life increases. Similarly, vehicle performance may increase as technological developments improve utility and public perceptions change. Perceptions will be influenced by information such as marketing and technology demonstration, and also by the number of vehicles already in use. Market potentials may increase by the market providing larger ranges of models across the vehicle classes (e.g. hybrid electric cars may in future be available more widely across the market segments). Thus for each new and alternative vehicle technology the change in P over time is modelled as an S-curve using a logistic function (Note: this is distinct from the S-curve of market penetration, i.e. vehicle numbers.). We assume that the new technology improves from a market entry year T_{entry} to a product maturity year $T_{maturity}$, reaching a maximum level P at maturity (Figure 3). T_{entry} is defined as the entry year for the first commercially available vehicles (albeit these may also be regarded as commercial prototypes, likely to be used primarily in demonstration projects). $T_{maturity}$ is the year when the vehicle technology performance and consumer preference are expected to level off (or at least become parallel with the trend line for conventional technologies).[4] P is estimated based on the expected relative market share of the new vehicle technology (in terms of new vehicle sales) in year T_2, compared to

---

[4] Note $T_{maturity}$ is not the date when market penetration (share of new vehicle sales) levels off for the new technology. Growth in new vehicle sales may lag behind the rise in P, as the number of sales will also be critically dependent on differences in technology costs and taxes.

some specified conventional comparator or reference technology, that might be anticipated if the annualised costs of the conventional and new technologies were the same. For instance, a medium gasoline car is the reference technology against which all new and alternative medium sized cars are compared with in terms of their expected performance, preference and market availability. If an alternative technology has the same performance and preference but is expected to lack the refuelling infrastructure even at market maturity then P is lower according to the relative shares in refuelling infrastructure coverage across the nation. Figure 3 illustrates this by showing four hypothetical curves comparing an existing reference technology to three new vehicle technologies with three different entry years, maturity years and levels of preference and performance.

Figure 3: Comparison of four hypothetical preference and performance parameter curves



Notes: P = preference and performance at market maturity; T_{entry} = expected entry year for the first commercially available vehicles; $T_{maturity}$ = expected maturity year i.e. year when the preference for and performance of the new vehicle technology are expected to level off (or at least become parallel with the trend line for existing technologies). T_{entry}1 is 2005 hence not shown in this Figure.

Vehicle technology 1 represents a rather slowly progressing conventional technology where market entry happened in the past and maturity is expected in 2015, e.g. a gasoline hybrid electric medium-sized car. Vehicle technologies 2 and 3 represent future technologies (with market entries of 2013 and 2019), with comparatively faster rates and at maturity higher expected performance and preference than technology 1. Technology 3 takes only 6 years to mature and even outstrips the reference technology.

Clearly the specification of future vehicle costs and P parameter curves are crucial to the medium to long term outcomes of the vehicle technology choice module. While default values for cost and non-cost parameters have been developed based on best available knowledge in the literature and in consultation with policy and industry experts, UKTCM users can modify them according to their market expectations or for simple ‘what-if’ analysis.

While the above methods apply to all vehicle categories, the car technology choice sub-module adds two further twists. New cars are modelled by size (defined by three engine size categories) and ownership (private and fleet/company). Over the last 10 years, the UK new car size split has been nearly constant, with small cars taking up around 25% of the market, medium 60% and large 15%. Small and medium car shares have fallen slightly over the past 10 years, while large cars have been on the increase. Vehicle size split is a scenario input variable so can be changed for future years for sensitivity analysis or exploration of scenario variants.

Car purchasing decisions can be quite different for the three main market segments of private, fleet and business car buyers. New fleet and business cars made up more than 50% of all new cars sold in 2007 and 2008 (DfT, 2009b; SMMT, 2009). The high share of fleet and business cars is largely a UK phenomenon. The UKTCM simulates this feature of the UK market by putting more emphasis on up-front costs in the private car model (high discount rate, or hurdle rate, of 30%) while the fleet buyer sees the commercial rate of 10%. The distinction makes it possible to simulate policies affecting different market segments (e.g. company car tax, scrappage rebate for private buyers).

3.4 Direct energy and emissions model (DEEM)

Approach

The VSM provides vehicle-kilometres and average trip lengths, disaggregated by passenger/freight, vehicle type, vehicle size, fuel type, propulsion technology (including engine and drivetrain technology, e.g. hybridisation) and 'route segment types' (such as urban, rural and motorway for road, urban/light and high speed for rail, and take-off and cruise for air). From this, the DEEM calculates fuel and energy consumption (in volume and energy units) as well as greenhouse gas pollutant emissions arising from the operation of vehicles by using the established emissions factor method. By modelling 'bottom-up' down to the level of vehicle technology and route segment type, the DEEM is able to model the combined effects of different fleet compositions, different sets of emission factors, traffic characteristics, cold starts, fuel quality and driver behaviour. This is a complex process and, given the focus of the paper, the detail has been omitted here but included in the UKTCM Reference Guide (Brand, 2010a).

Model specification, data sources and calibration

For road transport, speed distributions for each vehicle type (car, motorcycle, van, HGV) and route segment type (urban, rural, motorway) are used to calculate the energy consumption and emissions, based on average speed-emissions curves developed in previous research and emissions inventories such as COPERT (EEA, 1998, 2000), MEET (Hickman et al., 1999), HBEFA (INFRAS, 2004) and NAEI (NETCEN, 2003). These datasets provide a base set of emissions factors (mostly for conventional vehicle technologies), which is mapped onto UKTCM vehicle technologies and then scaled for future technologies – thus providing the default set of emissions factors for UKTCM. The user can change both mapping and scaling to simulate effects of policy such as fuel efficiency standards. Emissions factors for road vehicles at normal operating temperatures (often called 'hot') are a polynomial function of average speed, with up to ten coefficients for each pollutant. The UKTCM base emissions factors are based on HBEFA (INFRAS, 2004) coefficients, which were originally calibrated in extensive vehicle emissions testing. The road transport module also takes account of cold start effects. The default speed distributions are based on observed data for Great Britain (DfT, 2008c: Tables 7.10 and 7.11). To take account of effects such as congestion and speed limits the user can alter the speed distributions.

For all other modes, average emissions factors are used to calculate energy use and emissions. For air, emissions factors are split into the different flight stages 'landing/take-off' (LTO) and 'cruise'. The share of the LTO phase compared to the total flight distance is estimated based on the international CORINAIR/SNAP classification (code 08 05), where the flight distance up to an altitude of 1000 metres – about 30 km – is allocated to airport traffic.

Apart from direct energy use, the emissions types included in the DEEM are the direct greenhouse gases (GHG) carbon dioxide (CO_2) and methane (CH4) as well as the indirect GHG carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_X), non-methane volatile organic compounds (NMVOC) and particulates (PM).[5]

---

[5] Nitrous oxide (N_2O), the other direct GHG, is accounted for in the LCEIM.

As the methodologies used in the DEEM differ slightly from those used to derive national statistics, the DEEM needed to be calibrated in terms of energy use and emissions. The model was therefore calibrated to national statistics (DfT, 2008c) for each year between 1995 and 2007 by applying scaling factors to DEEM energy use and emissions factors.

3.5 Life cycle and environmental impacts model (LCEIM)

Approach

Based on a typical environmental life cycle assessment framework (ICO, 2006), the LCEIM comprises a life cycle inventory model and the environmental impacts assessment model. The life cycle inventory model calculates energy use and emissions (including primary energy and land use) for the manufacture, maintenance and disposal of vehicles; the construction, maintenance, and disposal of infrastructure; and the supply of energy (fuels). The environmental impacts assessment model then provides an assessment of the damage caused by calculating impact indicators (e.g. global warming potential) and external costs.

The life cycle inventory model uses the ‘hybrid approach’ of process-chain analysis and input-output analysis developed by Marheineke et al. (1998). Process chain analysis is used for the main supply paths, and aggregated values for complete process chains are used within the model. For additional upstream processes, considered to be second or third-order effects, input-output analysis is used. This hybrid approach is seen as appropriate as much of the evidence in the literature suggests that, in most cases, over the lifetime of a vehicle, vehicle operation produces the vast majority of energy use and

GHG emissions (Lane, 2006; MacLean and Lave, 2003). While the fuel supply and vehicle manufacture stages account for about 20% of total lifetime GHG emissions – being roughly equal in magnitude – vehicle maintenance and disposal account for a much smaller share (ibid.).

The environmental impacts assessment model converts direct (from the DEEM) and indirect (from the life cycle inventory model) emissions into impacts, which include a number of common impact indicators and external costs. Impact indicators are a means to describe environmental damage and to compare different pollutants with respect to a certain impact using different weighting factors. For example, the GWP_{100} (100-year Global Warming Potential) describes the warming impact of emissions over the next 100 years, and the POCP (Photochemical Ozone Creation Potential) refers to the formation of photochemical oxidants. The methodology for determining external costs is based on an evaluation of marginal effects. To estimate marginal effects an Impact Pathway Approach has been used, building on previous research on the European ExternE project (Bickel et al., 2003; EC, 2005).

The LCEIM allows the user to simulate the effects on energy use and emissions of e.g. adding new infrastructure (e.g. high speed rail), changes in the electricity generation mix and an alternative set of impact potentials (IPCC, 2007, is current default).

Model specification and data sources

The calculation of indirect emissions from the manufacture, maintenance and disposal of vehicles follows two main steps. First, each vehicle type (e.g. medium sized internal combustion car) is broken down into its components in terms of mass of materials needed to manufacture the vehicle and for vehicle maintenance (e.g. tyres, lubricants etc.). Some 15 materials are modelled for each vehicle, including alkyd resin varnish, aluminium, glass, polypropylene, rubber and three types of steel. Based on this materials breakdown, the emissions, primary energy use and land use changes embedded in each kg of material are derived, for up to 25 emissions categories including embedded CO_2, nitrous oxide (N_2O, a direct GHG), 'land use conversion from undeveloped to cultivated' (in metre square/kilogram of material) and 'crude oil' (in kilogram of oil/kilogram of material).[6] Secondly, the energy use and emissions for the processes involved in manufacturing, maintenance and disposal are derived by multiplying energy requirements for each process category with process emissions factors.

The calculation of indirect emissions for the construction, maintenance and disposal of additional infrastructure follows the same methodology as for life cycle assessment of vehicles.[7] The underlying data are based on a number of life cycle studies, where available based on UK context, including more generic inventories on fuels and

---

[6] For example, the embedded CO_2 emissions factors for unalloyed, low-alloy and high-alloy steel are 1.61, 1.97 and 5.28 kg of CO_2 per kg of material respectively. For aluminium this is even higher at 9.97 kg of CO_2 per kg of material.

[7] Emissions arising from maintenance of existing (road) infrastructure is not covered at present. Detailed infrastructure modelling would require an infrastructure-demand model to consider the effects of infrastructure changes on congestion or the effects of relatively higher road freight traffic on infrastructure maintenance. However, this is outside the scope of UKTCM as appropriate data and an infrastructure-demand model were not available.

powertrains (Brinkman et al., 2005; DTI, 2000; Joint Research Centre, 2006) and vehicle manufacturing and disposal (Lane, 2006; Schäfer et al., 2006; Zamel and Li, 2006) as well as more specific ones on vehicle materials (International Iron and Steel Institute, 2002), infrastructure materials (e.g. cement, Nemuth and Kreißig, 2007) and process emissions (e.g. freight transport, Höpfner et al., 2007). The allocation of emissions from additional infrastructure is done by vehicle-km, which presents a simplification as, for example, heavy trucks (doing fewer miles than cars overall) are responsible for a larger share of the damage. Double counting within the hybrid life cycle inventory was avoided as much as possible following Strømman et al. (2009).

Emissions from energy supply are calculated by converting energy and fuel use provided by the DEEM into emissions using well-to-tank emissions factors. Note in the case of biofuels, the DEEM calculates direct (or tank-to-wheel) emissions, while the LCEIM calculates well-to-tank emissions, which in the case of GHG may be negative (when growing the crops takes up more GHG from the atmosphere than fuel harvesting, production and distribution emits back into it). For electricity as a fuel, the LCEIM uses upstream emissions factors by generation fuel, taking into account the national electricity generation mix, transmission and distribution losses (around 10%) and imports from other countries (mainly France). In 2007, on an electricity supplied basis, 40% was generated by gas-fired power stations, 35% from coal, 16% from nuclear, 6% from renewables and 2% from imports (DECC, 2009). This results in a CO_2 content of electricity of 541 gCO_2/kWh end-use (including transmissions and distribution losses). The UKTCM incorporates default projections of the generation mix based on central Government projections to 2025 (DECC, 2008) and constant extrapolation to 2050. These can be changed by the user for scenario analysis.

Given the uncertainty inherent in life cycle assessment, the differences in methods, assumptions and data used in these studies, default data were chosen for the LCEIM that represent ‘best estimates’, which can be changed by the user.

As for impact indicators, the LCEIM applies a simplified impact pathway approach using a building block methodology. This uses aggregated parameterised values for different processes and technologies that are based on (a) atmospheric transport and chemical transformation modelling; (b) calculation of concentrations/depositions, and (c) application of dose-response relationships. The building blocks provide a transformation between input parameters (such as emissions) and external costs. They also allow a transition from marginal to absolute effects. Different methodologies are applied for the direct emissions from vehicles and for indirect emissions from up- and downstream processes.

The following two sections bring the model alive by presenting the results policy scenario analysis involving a reference scenario and four alternative policy scenarios for comparison.

4 A REFENCE SCENARIO FOR COMPARISON

4.1 Approach

To assess the likely effects of changes in policy and strategy against some reference situation, a ‘reference scenario’ for the outlook period up to 2050 is required. This reference scenario should not be confused with a ‘business-as-usual’ forecast. It can be defined by the user in many ways, for example based on government projections or alternative images of the future. The reference scenario developed for this research is broadly a projection of transport activity, energy use and emissions as if there were no policy action (unless policies already exist or are ‘firm and funded’, in which case their impact is reflected in the reference scenario). For cars, the reference scenario assumes there is no further policy, that is, no policy following on from the EU Voluntary Agreements (VA), which end in 2008-09. A mandatory successor to the VA has been proposed but details of the scheme are still being worked out. For vans and HGVs it is assumed that these modes continue to be outside of the EU framework for targets on new vehicle emissions. Based on the UK’s Renewable Transport Fuels Obligation (RTFO), the reference scenario includes biofuels use for road transport increasing to about 4% by energy (5% by volume) by 2013, remaining fixed at that level for future years.[8]

4.2 Key data sources and assumptions

The reference scenario was built around current demographic, economic and demand projections. Economic growth up to 2011 is based on UK government figures and near term forecasts (HM Treasury, 2008), including the 2008/09 recession. From 2012 GDP growth is assumed to average 2.0% up to 2050 – in line with the historic 50-year

---

[8] The EU also proposed, in January 2008, a mandatory target for biofuels for Member States of 10% by energy in 2020. In July 2008, the Gallagher Review of the Indirect Effects of Biofuels RFA, 2008. The Gallagher Review of the indirect effects of biofuels production. Renewable Fuels Agency (RFA), St Leonards-on-Sea. collated the latest evidence on biofuels sustainability and greenhouse gas impacts. As a result of the Gallagher Review, the UK and EU targets are both open to change. It was therefore decided to use the Gallagher recommendations, rather than previous policy commitments in the reference projection.

average for the UK. Population projections are based on national population trends and forecasts (ONS, 2008). Energy resource (oil, gas, biomass, etc.) price projections are based on ‘central’ government forecasts[9] (DECC, 2008), with the central forecast projecting the real term oil price to average 65 US$(2007) per barrel in 2010, then rising slightly to 70 US$(2007) per barrel by 2020 and increasing further to 75 US$(2007) per barrel in 2030. Our reference scenario then extrapolates to 2050 where crude oil is forecast to cost 85 US$(2007) per barrel. While household disposable income is assumed to grow in line with economic growth, the urban/non-urban split of household location is kept constant at 2008 levels. Average vehicle load factors are assumed to remain constant at 2008 levels. Vehicle and fuel taxes as well as maintenance and insurance costs of all vehicle types are assumed to remain constant at current levels. While pre-tax vehicle purchase costs were kept constant over time for established technologies, they gradually decrease for unconventional and future technologies, thus exogenously simulating improvements in production costs. For future vehicle technologies, the preference and performance parameters were developed in consultation with policy makers and industry experts, as mentioned earlier. For example, the ratio of the preference and performance parameters for the average medium sized gasoline plug-in hybrid electric (PHEV) car and its reference technology, the medium sized gasoline car, is gradually increasing from 0.3% for the 2009-14 vintage to a maximum of 10% for the 2030 vintage and any further vintages. The main reasons for the relatively low values and gradual rate increase assumed in the reference

---

[9] The published official forecast by DECC serves as a reference against which alternative futures should be compared with, in particular in the light of accelerating depletion of oil resources. Alternative scenarios could be run based simply on different resource price projections.

scenario are (a) limited deployment of the charging infrastructure (e.g. only in future ‘low carbon cities’), (b) relatively limited market availability of PHEV cars and (c) consumer preference for ‘conventional’ over ‘new/unknown’ technology. The 10% figure for market presence is in the same ballpark as what some car manufacturers want us to believe. Nissan’s chief executive, Carlos Ghosn, was quoted by the BBC as predicting: *“The electric car will account for 10% of the global market in 10 years.”* (BBC News, 2010) – a somewhat optimistic view. The reference case thus assumes a slower rate of improvement for the preference factor, lagging behind by a decade or so. Similarly, road vehicles running on high blend biofuels (e.g. E85) have a relatively low preference factors (about 2% of the reference technology) due to the limited development of refuelling stations assumed in the reference case.

Operating the UKTCM in simulation mode, transport demand projections were exogenously aligned to government projections. For road and rail, this was based on the ‘central’ forecast of the National Transport Model (DfT, 2008b) to 2025 and extrapolated to 2050. The ‘business-as-usual’ projections in Kollamthodi et al. (2008) were used for shipping, and air transport projections were based on the most recent capacity constrained ‘s12s2’ demand forecast in DfT (2009a). These projections imply gradually lower growth rates for most vehicle types. For instance, the car passenger-km growth rate between 2010 and 2020 is 0.78% p.a. (i.e. lower than the 0.97% p.a. between 2000 and 2005), decreasing to around 0.4% p.a. for the 2040-2050 period. Air travel (domestic and international) is expected to grow by 3.1% p.a. for the 2010-2020 period, gradually decreasing to 0.7% p.a. for the 2040-2050 period. Therefore, the reference case implies that air travel is set to decouple from GDP and income and (more or less) saturate by the middle of this century.

The reference scenario assumes gradual improvements in specific fuel consumption (in unit of fuel per km travelled) and tailpipe CO_2 emissions for all vehicle types including cars, vans, trucks, shipping vessels and aircraft. The rates of improvement vary by vehicle type, size and propulsion technology and are based on technological innovation alone, not on policy or regulatory push (e.g. voluntary/mandatory agreement on new car CO_2 emissions). For example, the fuel consumption improvement rates for new conventional, hybrid and plug-in hybrid cars are assumed to be around 0.5% p.a. – a lower rate than the average rate of 1.3% p.a. observed for new cars between 2000 and 2007 (SMMT, 2008). The assumed specific fuel consumption figures for 2010 and rates of improvements up to 2050 are shown for cars in Table 4.

Table 4: Summary list of specific fuel consumption figures and rates of improvements for cars for the reference scenario

		SFC [a]	**Average rates of change (% p.a.)**		
Car size	**Fuel / engine technology**	**2010 baseline**	**2010 - 2020**	**2020 - 2030**	**2030 - 2050**
Small	Gasoline ICV	7.3	-0.5%	-0.5%	-0.5%
	Gasoline PHEV	5.1	-0.5%	-0.5%	-0.5%
	Diesel ICV	4.9	-0.5%	-0.5%	-0.5%
	Battery EV	16.5 (1)	-0.8%	-0.8%	-0.5%
	H_2 FC	12.3 (2)	-	-2.1%	-1.1%
Medium	Gasoline ICV	8.3	-0.5%	-0.5%	-0.5%
	Gasoline HEV	5.0	-0.5%	-0.5%	-0.5%
	Gasoline PHEV (3)	5.8 (15)	-0.5%	-0.5%	-0.5%
	Diesel ICV	5.4	-0.5%	-0.5%	-0.5%
	Diesel HEV	3.3	-0.5%	-0.5%	-0.5%
	B100 ICV	4.3	-1.4%	-0.7%	-0.5%
	E85 ICV	8.7	-0.5%	-0.5%	-0.5%
	LPG ICV	12.7	-0.5%	-0.6%	-0.6%
	H_2 FC	20.5 (2)	-	-1.4%	-0.7%
Large	Gasoline ICV	10.3	-0.5%	-0.5%	-0.5%
	Gasoline HEV	6.2	-0.5%	-0.5%	-0.5%
	Gasoline PHEV (3)	7.2 (23)	-0.5%	-0.5%	-0.5%
	Diesel ICV	7.0	-0.5%	-0.5%	-0.5%
	Diesel HEV	4.2	-0.5%	-0.5%	-0.5%
	B100 ICV	6.8	-1.4%	-0.7%	-0.5%
	E85 ICV	10.7	-0.5%	-0.5%	-0.5%
	LPG ICV	13.8	-0.5%	-0.6%	-0.6%
	H_2 ICV	43.8	-1.0%	-1.2%	-0.6%
	H_2 FC	20.5 (2)	-	-1.4%	-0.7%

Notes: [a] SFC = specific fuel consumption as an average over urban, rural and motorway driving cycles and including cold starts, expressed in litres per 100km for all fuels except electricity, where SFC is expressed in kWh per 100km. (1) SFC is in kWh/km. (2) FC figure is for 2020. (3) For PHEV, the first SFC figure is for the liquid energy carrier, expressed in l/100km and representing the weighted average of rural and motorway driving cycles; the second SFC figure in brackets is for electric operation, expressed in kWh/100km and representing urban driving cycle.

4.3 Reference scenario results

The demand for domestic passenger transport (in passenger-km) is projected to increase by 10% by 2020 and 21% by 2050 from 2007 levels (Table 5). Travel by car continues to dominate passenger transport, with shares of 80% in 2020 and 77% in 2050. Rail and bus see their shares increase slightly to 11% and 8% in 2050 respectively. While domestic air travel accounts for only around 2% of total domestic passenger transport, international passenger air travel adds to this considerably (up to 70% by 2050) and from a 2007 baseline increases by 39% and 115% by 2020 and 2050 respectively. Domestic freight transport (in tonne-km) is set to increase by 19% by 2020 and 73% by 2050. Domestic freight transport continues to be dominated by road freight (62% in 2020, 58% in 2050), yet rail freight is expected to increase its share from 10% in 2007 to 16% in 2050.

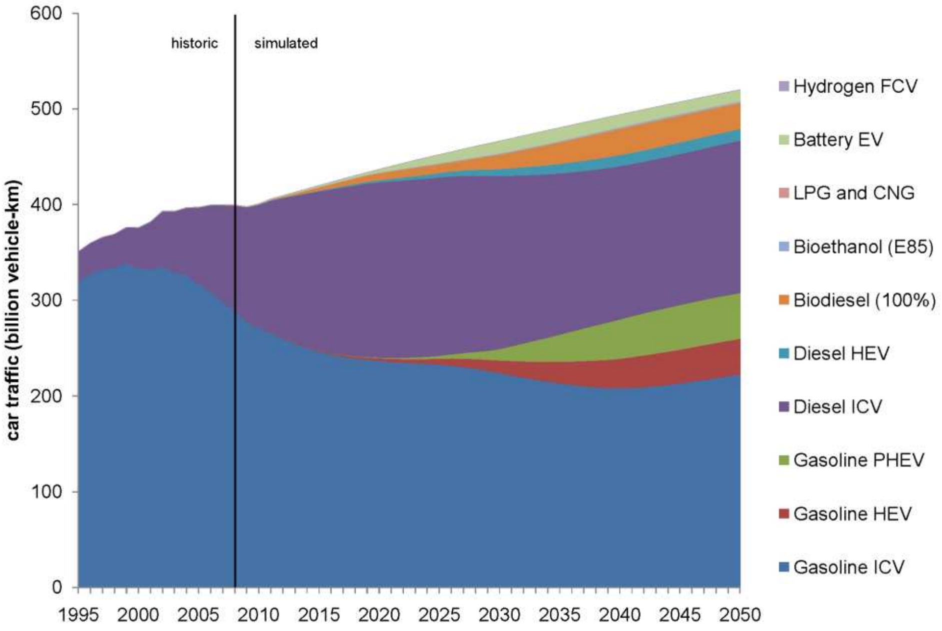
As there are no major changes assumed in passenger and freight load factors over time, these trends are mirrored in traffic projections (vehicle-km). For road traffic, the highest rate of increase is expected for light goods vehicles (LGV, or vans), nearly tripling from 66.4 billion vehicle-km in 2007 to 185.3 billion vehicle-km in 2050. Over the same period car traffic increases by only 30%, heavy goods vehicles (HGV) traffic by 22% and rail traffic doubles. Gasoline and diesel continue to be the main fuels used for road transport, mainly because the price of fuels does not increase significantly and alternative fuels (and vehicles) are neither widely available nor preferred by consumers.

Table 5: Selection of the main output indicators projected for the reference scenario

	projected figures for key dates					average annual growth rates (%)		
Traffic (billion vkm)	2007	2015	2020	2030	2050	2010-2020	2020-2030	2030-2050
Motorcycle	6.3	7.0	7.4	7.6	7.0	1.6%	0.2%	-0.4%
Car	399.9	420.1	437.0	466.5	520.2	0.9%	0.7%	0.5%
Bus and coach	5.9	6.2	6.3	6.5	6.9	0.6%	0.3%	0.3%
LGV	66.4	82.3	94.8	122.2	185.3	3.0%	2.6%	2.1%
HGV	29.1	30.2	31.4	33.4	35.6	0.9%	0.6%	0.3%
Urban rail (LRT, metro)	0.1	0.1	0.1	0.1	0.2	1.9%	1.6%	1.4%
Regional and Intercity	0.6	0.6	0.7	0.8	1.1	2.1%	1.8%	1.5%
High Speed	0.0	0.0	0.0	0.0	0.0	1.9%	1.6%	1.4%
Navigation, domestic	0.0	0.0	0.0	0.0	0.0	1.6%	1.4%	1.1%
Aircraft, domestic	0.2	0.2	0.3	0.3	0.4	3.1%	2.1%	1.1%
Aircraft, international	2.1	2.6	3.0	3.7	4.7	3.0%	2.2%	1.2%
New cars (thousand vehicles)								
Gasoline ICV	1157	1407	1399	1306	1581	0.6%	-0.7%	1.0%
Diesel ICV	937	1099	1128	1010	1101	1.0%	-1.1%	0.4%
Gasoline & diesel HEV	7	31	71	237	343	21%	13%	1.9%
Gasoline & diesel PHEV	0	2	11	237	335	55%	36%	1.7%
Battery EV	4	21	71	86	80	25%	2.0%	-0.4%
LPG & CNG	1	1	1	2	3	0.4%	4.6%	2.9%
Biodiesel & -ethanol	1	68	65	205	193	24%	12%	-0.3%
Fuel cell H2	0	0	0	0	1	43%	10%	7.1%
Total new cars	2107	2630	2746	3083	3636	1.5%	1.2%	0.8%
Direct CO_2 (at source) (million tonnes)								
Motorcycle	0.6	0.6	0.6	0.6	0.5	-0.5%	0.1%	-0.4%
Car	76.9	74.0	73.1	70.2	67.2	-0.2%	-0.4%	-0.2%
Bus and coach	3.2	3.1	3.0	2.7	2.2	-0.2%	-1.0%	-1.0%
LGV	14.5	17.0	18.9	22.2	30.0	2.3%	1.6%	1.5%
HGV	26.3	25.8	25.8	25.6	25.2	0.1%	-0.1%	-0.1%
Rail, diesel only	2.2	2.2	2.2	2.3	3.0	0.4%	0.3%	1.3%
Navigation, domestic	2.4	2.6	2.8	3.0	3.7	1.1%	1.0%	1.1%
Aircraft, domestic	2.2	2.4	2.6	2.9	3.1	1.8%	1.1%	0.3%
Aircraft, international	35.5	39.8	42.6	47.4	50.4	1.8%	1.1%	0.3%
Total domestic	128.4	127.7	129.0	129.5	134.9	0.2%	0.0%	0.2%
Lifecycle CO_2 (million tonnes)								
Motorcycle	0.7	0.7	0.7	0.7	0.6	-0.4%	0.1%	-0.4%
Car	107.6	107.0	106.7	106.2	106.4	0.0%	0.0%	0.0%
Bus and coach	4.1	3.9	3.8	3.6	3.3	-0.2%	-0.5%	-0.5%
LGV	21.0	24.7	27.4	32.5	44.7	2.6%	1.7%	1.6%
HGV	33.9	33.1	33.1	32.5	32.1	0.2%	-0.2%	-0.1%
Rail, diesel only	5.2	5.4	5.5	5.8	7.4	0.9%	0.5%	1.2%
Navigation, domestic	2.6	2.8	3.0	3.2	4.0	1.2%	0.8%	1.0%
Aircraft, domestic	2.6	3.0	3.2	3.5	3.8	1.8%	1.1%	0.4%
Aircraft, international	43.6	48.9	52.4	58.6	62.8	1.8%	1.1%	0.3%
Total domestic	177.7	180.6	183.4	188.1	202.2	0.5%	0.3%	0.4%

The historic and projected domestic traffic by primary fuel and hybridisation is shown for cars in Figure 4, suggesting that pure biodiesel ICV and BEV cars will gradually increase market shares but be limited to a few percent of total traffic while first HEV then PHEV cars will take a larger share of the market from about 2020 onwards. Although not shown in the Figure, rail sees a moderate shift towards electrified rail, with a 64% share of total traffic by 2050.

Figure 4: Historic and projected domestic car traffic by primary fuel and hybridisation, reference scenario

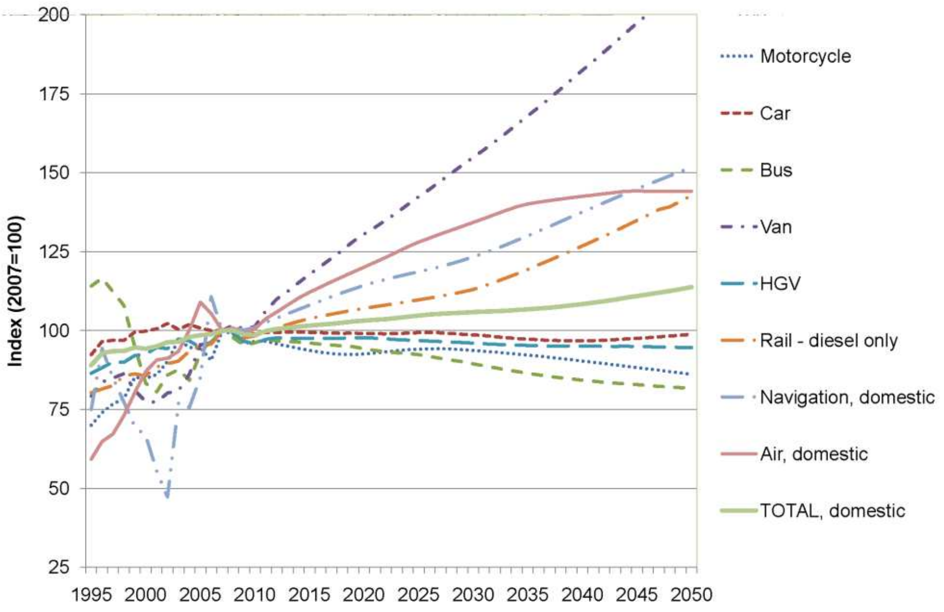


Notes: E85 = blend of 15% petrol and 85% bioethanol; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; ICV = internal combustion engine vehicle; FCV = fuel cell vehicle; LPG = liquefied petroleum gas; CNG = compressed natural gas

Car ownership increases as a result of population growth, increased household disposable incomes, lower average new car purchase prices in real terms and comparatively lower availability of public transport in rural areas. Assuming that car scrappage rates do not change over the outlook period, this results in the demand for new cars rising from about 2.1 million in 2007 to over 3.6 million in 2050. Only 3% of new cars are expected to be electric (either BEV or PHEV) in 2020, rising to about 12% by 2030 and then levelling out. This is a direct result of the price differentials for each technology and the limitations imposed on the preference and performance factor for BEV and PHEV explained earlier.

Direct CO_2 emissions from domestic transport increase slightly by about 5% between 2007 and 2050, while indirect (i.e. upstream and downstream) CO_2 emissions rise by 37% over the same period. This can be explained by a moderate shift towards electric road and rail transport. On the back of rising traffic, direct CO_2 emissions from cars actually fall by 5% by 2020 and 13% by 2050, mainly due to fuel economy improvements and the increased uptake of electric (BEV and PHEV) cars that produce no emissions at source. Electric vehicles obviously produce emissions upstream from electricity generation. Add this to the upstream and downstream emissions from the increase in car numbers and scrapped vehicles over time, indirect CO_2 emissions from cars increase by 8.5 million tonnes (28%) between 2007 and 2050. As a result, lifecycle (direct plus indirect) emissions of CO_2 from domestic traffic increase by 14% between 2007 and 2050 while emissions from cars stay about the same (Figure 5). Although not shown in the Figure, lifecycle CO_2 emissions from international air travel increase by 20% between 2007 and 2020 and 44% by 2040 when they reach a plateau. This is mainly due to the combined effects of improved fuel economy of future aircraft and lower aviation growth rates by the middle of this century.

Figure 5: Historic and projected lifecycle CO_2 emissions from domestic transport by vehicle type, reference scenario (index 100 = year 2007)



As for the non-CO_2 GHG, the picture is mixed. While CH_4, CO, NO_X and NMVOC emissions decrease significantly by 2030 and then stay roughly constant, emissions of N_2O increase due to the increased use of biofuels. The lifecycle GWP_{100} increases by 2% and 14% between 2007 and 2020 and 2050 respectively. As this is similar to the CO_2 emissions projections the different impacts of non-CO_2 emissions seem to cancel each other out.

5 ALTERNATIVE SCENARIOS

To illustrate the variety of policy scenario analyses that can be handled by UKTCM the results of four alternative ‘what if’ type scenarios are presented here. The illustrative scenarios are (a) a private vehicle fuel duty policy with emphasis on ‘early action’ (FD1), (b) effective speed limit enforcement on motorways and dual carriageways (SPE1), (c) a technology promotion and incentivisation programme that affects consumer preferences, market availability and costs of EV and PHEV cars (EV1), and (d) an integrated policy package (PP1) comprising the three single policy scenarios.

5.1 Policy description and assumptions

In fuel duty scenario FD1 “early action” is followed by “gradual but little action”: road fuel duties on petro-fuels (petrol, diesel, compressed natural gas, liquefied petroleum gas) and bio-fuels (100% bio-diesel, 85% bio-ethanol) for cars and motorcycles[10] double between 2010 and 2020, with further but less steep increases of 1 pence/litre per year from 2021 onwards. Further taking into account resource cost increases due to forecast crude oil price rises, average petrol and diesel prices are set to double between 2010 and 2050. In scenario SPE1 it is assumed that by 2014 the current 70 mph (113 kph) speed limit is effectively enforced for all road vehicles on both motorways and dual carriageways. This is modelled by gradually changing the speed profile for road vehicles. It effectively reduces average speed for cars and motorcycles on motorways

---

[10] In this scenario the fuel duties for buses, vans, HGV and all other surface passenger transport modes remain untouched. Similarly, the policy of no fuel duty or value added tax on aviation fuel remains unchanged.

from 69 mph (111 kph) to 57 mph (91 kph). Average speeds for vans, HGV and coaches effectively decrease from 56 mph (90 kph) to 54 mph (87 kph). No demand effects are assumed in SPE1. In scenario EV1, electric vehicles (first HEV, then BEV and PHEV) are becoming more widely available, gradually increase their performance relative to ICV vehicles and, crucially, will be equally preferred by consumers when compared to their ICV counterparts.[11] The necessary recharging stations will be built in urban areas together with smart metering and home charging. This systemic change is assumed to happen gradually over the next 10-20 years. The integrated package PP1 comprises the three options above, essentially simulating a road transport policy scenario with early action on petro- and bio-fuel duty and effective speed limit enforcement supplemented by partial electrification of road transport in medium to long term.

5.2 Main results

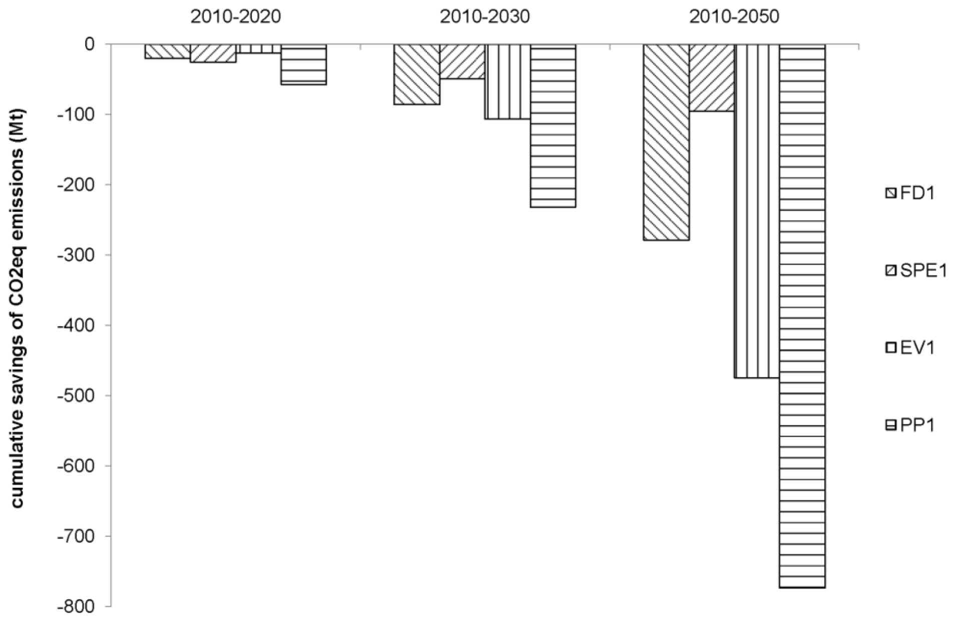
The fuel duty scenario (FD1) results in a 7% higher cost of motoring by car in 2020 than in the reference case (REF), and 8% higher in 2050. As a result, passenger car demand is 3% lower in 2020 and 4% lower in 2050 than the baseline projection. There is some (<1%) modal shift to bus, rail and short haul air, and overall domestic demand

---

[11] This is modelled by using an alternative set of preference and performance parameter (P) curves for cars, vans, HGV and buses on the principle that by a certain maturity year EVs (BEV, HEV, PHEV) are on equal terms with their reference technologies (petrol or diesel ICV) in terms of consumer preference, performance (max. speed, acceleration, range) and market potential/choice (equal presence on the market, not just a few exceptions as in 2009). It is further assumed that there is no change in the default forecast for the electricity generation mix.

for passenger travel decreases by 2% and 3% in 2020 and 2050 respectively. Although the total number of cars is only marginally lower in 2020 and 2050 than baseline, the car fleet sees a moderate shift from gasoline ICV technology to diesel/biodiesel ICV and electric cars (mainly BEV). By 2020, diesel will overtake gasoline as the main choice of fuel for new cars, and 11% of new cars will feature an electric drivetrain (BEV, HEV, PHEV), increasing to 31% by 2050. The combined effects of demand reduction, modal shift and moderate technology change results in 5% (2020) and 15% (2050) lower direct CO_2 emissions from car travel in the FD1 scenario than in the REF case. Total lifecycle emissions of CO_2 equivalent (CO_2^{eq}, based on 100-year global warming potential) are also lower by 4% (2020) and 10% (2050) when compared to baseline levels. Cumulatively, the fuel duty policy (FD1) saves around 20 million tonnes (Mt) of CO_2^{eq} between 2010 and 2020, and 279 Mt between 2010 and 2050 when compared to baseline (Figure 6). While the demand for petro-fuels decreases slightly (from 52 billion litres in 2007 to 47 billion litres in 2050), the demand for electricity for transport quadruples between 2007 and 2050 (30% higher than in the REF case) – mainly as a result of the uptake of plug-in (BEV, PHEV) cars. The energy system-wide modelling of the aforementioned Energy2050 study (Anable et al., forthcoming; UK Energy Research Centre, 2009) suggests that overall the projected generation capacity and the electricity grid could cope with this increased demand if the vehicles were mainly charged overnight. The devil, however, may lie in the detail. It is still unclear whether the UK’s low voltage grid could cope at peak times, e.g. early evening when ovens, kettles, water/space heating and EV charging may prove too much, thus requiring investment in the grid on a large scale. One option to manage demand and deal with the different tax regimes is to have dual smart meters (one for transport, one for household electricity) and clear pricing signals that make it cheaper (more expensive) to charge at off-peak (peak) times. Potentially most attractive for government are the 55% (2020) and 64% (2050) higher revenues from road fuel taxation.

Figure 6: Scenario comparison of cumulative savings of CO_2^{eq} emissions when compared to the reference case (REF)

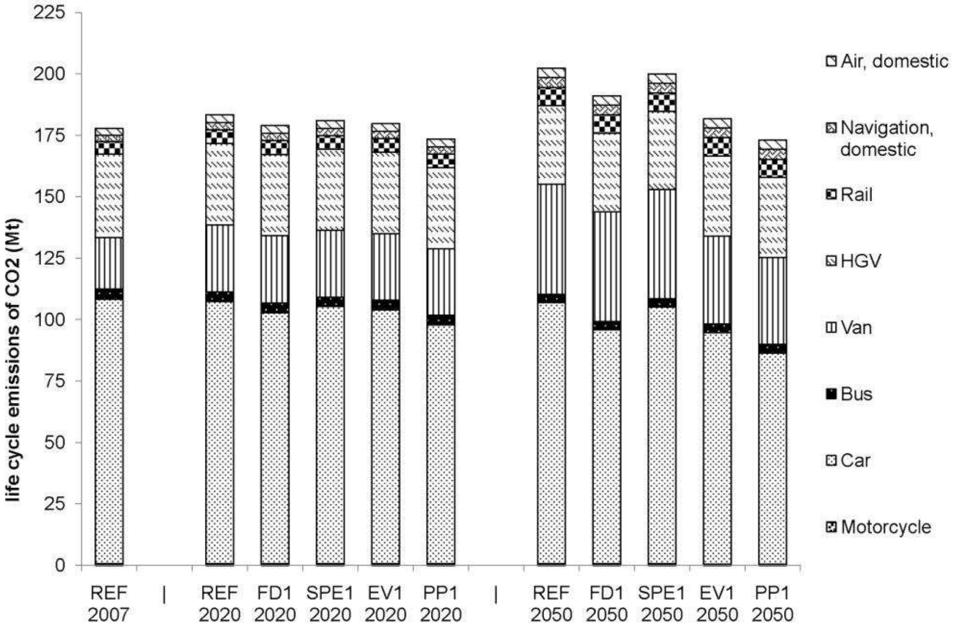


In the speed enforcement scenario (SPE1), the lower average speeds on motorways result in 2.3% (2020) and 2.4% lower direct CO_2 emissions from all car travel (not just motorways) than in the reference case (REF). Emissions from motorcycle, van and HGV travel are also reduced, but less so. This results in a 1.5% reduction in UK domestic CO_2 emissions when compared to baseline levels from 2015 onwards.

Cumulatively, the speed enforcement policy (SPE1) saves around 20 Mt of CO_2^{eq} between 2010 and 2020, and 96 Mt between 2010 and 2050.

The EV1 scenario emerges as a good low carbon option for the medium to long term. While in the REF case only 3% of new cars will be plugged (BEV, PHEV) by 2020, rising to 11% by 2030 and then levelling off, the EV1 scenario projects a higher rate of take up from about 2018, with 30% and 51% of new cars being electric by 2030 and 2050 respectively. Interestingly, the demand for road traffic increases when compared to baseline – a result of the lower overall cost of 'electric' motoring (NB: no duty on electricity for transport use was assumed). Nevertheless, from 2020 onwards direct CO_2 emissions follow a considerably lower trajectory than in the REF case, while indirect emissions (mainly from electricity generation, but also vehicle production) are higher. By 2030, lifecycle CO_2 emissions from domestic transport are 7% lower in the EV1 scenario than in the REF case, and 10% lower by 2050 (Figure 7). While the demand for electricity for domestic transport is projected to be 2.5 times higher in the long term than in the REF case (reaching 35 TWh by 2050), the demand for petro- and bio-fuels is naturally lower, thus providing the taxman £5.4 billion p.a. (21%) less revenue from fuel duty by 2050. Cumulatively, the EV1 scenario saves 107 Mt of CO_2^{eq} between 2010 and 2030, and 474 Mt between 2010 and 2050.

Figure 7: Scenario comparison of total lifecycle CO_2 emissions from domestic transport by vehicle type for 2007, 2020 and 2050



In the integrated scenario (PP1), the combined effects of fuel duty increases, speed limit enforcement and partial electrification of road transport result in marginally lower demand for passenger transport (-2% in 2020, -1% in 2050) than in the REF case. Private vehicle traffic is reduced accordingly (-1.5% in 2050 compared to baseline), but not as much as in the fuel duty scenario (FD1). The shift from gasoline and diesel/biodiesel ICV technology to HEV and plug-in electric cars is more pronounced than in any of the single policy scenarios. By 2050, only 17% of new cars in PP1 will be gasoline or diesel/biodiesel ICV, 30% will be gasoline or diesel HEV, 39% PHEV and 14% BEV. Direct CO_2 emissions from domestic transport fall below 100 Mt by about 2030 (23% less than in 2007) but see an increase again after 2040 due to increased demand. Still, this is 8% (2020) and 27% (2050) less than in the reference case. Similarly, in PP1 total lifecycle CO_2 and CO_2^{eq} from domestic transport decrease in the medium term followed by a gradual increase to roughly where we are now in the long term (Figure 7) – yet this is 5% (2020) and 14% (2050) less than baseline (REF) levels. Cumulatively, the PP1 policy package saves around 57 Mt of CO_2^{eq} between 2010 and 2020, and 773 Mt between 2010 and 2050 (Figure 6). As a result of the fuel switching, the demand for petro-fuels decreases significantly (from 52 billion litres in 2007 to 38 billion litres in 2050), but revenues from road fuel taxation are still 24% higher than in the REF case due to the doubling of petro-fuel duty. In contrast the demand for electricity for domestic transport increases tenfold between 2007 (about 4 TWh) and 2050 (about 39 TWh), which has potentially major implications for electricity load management and recharging regimes.

6 CONCLUSIONS

This paper starts with the premise that there is a lack of integrated scenario modelling capability for research and practice that is appropriate for modelling the wide range of policies needed to decarbonise the transport system. It then aims to fill that gap by presenting a newly developed strategic transport-energy-environment model, the UKTCM, which is complementary to more sophisticated forecasting models (which usually address more specific aspects of the transport-energy-environment system but not the whole system). As a simulation model it is primarily aimed at 'what-if' type policy analyses and low carbon strategy development for the medium to long term. Although it comprises elements of forecasting at the aggregate levels, the model is not suited to endogenously model, say, the finer details of 'smarter choices' policies.

However, the scenario modelling framework is suited for developing structured ‘storylines’ and breaking down current travel choices into their constituent journey purposes, lengths and modes as scenario inputs. Arguably the forecasting of the long term future beyond say 2020 based on historic values, habits and norms is not an appropriate approach – hence the more flexible scenario approach adopted here.

By its nature as a simulation tool, UKTCM does not include the general equilibrium modelling and interaction with economy-wide variables (such as the feedback from transport fuel prices into effects on GDP and household income). There is partial equilibrium, however, in that average transport costs for each mode feedback to the demand model. The model is a sectoral model looking primarily at the energy and environmental impacts of the movement of people and freight. Although it includes effects such as emissions from electricity generation as well as embedded energy use and emissions from vehicle production, it is not an energy systems model. UKTCM can be, and indeed has been, linked with energy systems models such as MARKAL to provide insights into the linkages with and cross-sectoral trade-offs within the energy system. An example is the recent Energy2050 work of the UK Energy Research Centre (Anable et al., forthcoming; UK Energy Research Centre, 2009) where UKTCM played a key role in developing the ‘Lifestyle’ scenarios.

One of the central challenges for policy makers is to prioritise limited resources in order to target the most effective policy interventions. As demonstrated above, the UKTCM is unique in its ability to model a number of discrete policies as well as integrated policy packages over different time horizons. For instance, it was shown that in terms of prioritizing policy interventions, speed enforcement emerged as the ‘winner’ over the short-term (2010-2020), with fuel duty and electric vehicles pulling ahead over the medium-term (2010-2030). However, over the long-term (2010-2050), electric vehicles appear to be the most effective single strategy for reducing emissions. Nevertheless, what is clear from the analysis is that an integrated policy approach that considers both demand and supply side strategies are far more effective than any single policy intervention and therefore necessary for achieving a stringent 80% carbon emissions reduction target. The UKTCM can therefore inform decision-makers through comparative analysis of single policies or against integrated strategies of energy and transport policy interventions. Importantly, the model can give insight into what priorities should be given to different policy interventions over variable time-scales.

7 ACKNOWLEDGMENTS

This research was funded by the UK Research Councils (Grant No: NERC NE/C513169) as part of the Demand Reduction Theme of the UK Energy Research Centre (UKERC). The authors would like to thank the two anonymous referees for their helpful and constructive comments that have greatly improved the original manuscript.

8 REFERENCES

Anable, J., Brand, C., Tran, M., Eyre, N., forthcoming. Modelling transport energy demand: a socio-technical approach. Energy Policy.

BBC News, 2010. Nissan Leaf electric car to be built in Sunderland, last accessed at http://news.bbc.co.uk/1/hi/business/8573724.stm on 18/03/10. BBC, London.

Bickel, P., Schmid, S., Tervonen, J., Hämekoski, K., Otterström, T., Anton, P., Enei, R., Leone, G., van Donselaar, P., Carmigchelt, H., 2003. Environmental Marginal Cost Studies. Deliverable 11 UNITE. European Commission 5 th Framework Transport RTD.

Brand, C., 2010a. UK Transport Carbon Model: Reference Guide v1.0. UK Energy Research Centre, Energy Demand Theme, Oxford.

Brand, C., 2010b. UK Transport Carbon Model: User Guide v1.0. UK Energy Research Centre, Energy Demand Theme, Oxford.

Brinkman, N., Wang, M., Weber, T., Darlington, T., 2005. Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems - A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions. Argonne National Laboratory, Transportation Technology R&D Center, Argonne (IL).

Burgess, A., Becker, J.F.F., Snelder, M., Bröcker, J., Schneekloth, N., Szimba, E., Kraft, M., Krail, M., Nielsen, O., Hansen, C., Martino A., Fiorello, D., Christidis, P., Chen, M., Vilcan, A., Tardieu, P., 2005. Report on Policy Requirements and Selected Relevant Models/Methods, TRANS-TOOLS Deliverable 1, Funded by 6th Framework RTD Programme. TNO Inro, Delft, The Netherlands.

CCC, 2009. Meeting carbon budgets – the need for a step change. Progress report to Parliament. Committee on Climate Change (CCC), London.

CfIT, 2007. Transport and Climate Change. Commission for Integrated Transport, London.

Clements, K.W., 2008. Price elasticities of demand are minus one-half. Economics Letters 99, 490-493.

De Ceuster, G.E., Van Herbruggen, B., Logghe, S., Proost, S., 2004. The TREMOVE 2.0 Model Description. Transport & Mobility Leuven and K.U. Leuven for the European Commission, DG ENV, Directorate C, Leuven and Brussels.

de Jong, G., Gunn, H., Ben-Akiva, M., 2004. A meta-model for passenger and freight transport in Europe. Transport Policy 11, 329-344.

DECC, 2008. Updated Energy and Carbon Emissions Projections: November 2008, last accessed at http://www.berr.gov.uk/files/file48514.pdf on 18/09/2009. Department of Energy and Climate Change, London.

DECC, 2009. Digest of United Kingdom Energy Statistics (DUKES) 2009 edition. Department of Energy and Climate Change (DECC), The Stationary Office, London.

DETR, 1997. National Road Traffic Forecasts (Great Britain) 1997. Department of the Environment, Transport and the Regions, The Stationary Office, London.

DfT, 2005. National Transport Model - Working Paper 2, last accessed at http://www.dft.gov.uk/pgr/economics/ntm/pdfnatransmodwp2.pdf on 05/11/09. Department for Transport (DfT), London.

DfT, 2008a. Carbon Pathway Analysis, Full Report. Department for Transport (DfT), The Stationary Office, Office, T.S., London.

DfT, 2008b. Road Transport Forecasts 2008. Department for Transport (DfT), The Stationary Office, London.

DfT, 2008c. Transport Statistics Great Britain: 2008 edition. Department for Transport (DfT), The Stationary Office, London.

DfT, 2009a. UK Air Passenger Demand and CO2 Forecasts. Department for Transport (DfT), London.

DfT, 2009b. Vehicle Licensing Statistics: 2008. Department for Transport (DfT), The Stationary Office, London.

DTI, 2000. The Report of the Alternative Fuels Group of the Cleaner Vehicle Task Force. Department of Trade and Industry (DTI), The Stationary Office, London.

EC, 2005. ExternE: Externalities of Energy, Methodology 2005 Update. European Commission, Directorate-General for Research, Sustainable Energy Systems, Brussels.

EEA, 1998. COPERT II: Computer Programme to calculate Emissions from Road Transport, Users Manual. European Topic Centre on Air and Climate Change, European Environment Agency (EEA), Copenhagen.

EEA, 2000. COPERT III: Computer Programme to Calculate Emissions from Road Transport - Methodology and Emission Factors (Version 2.1), Technical report No 49. European Topic Centre on Air and Climate Change, European Environment Agency (EEA), Copenhagen.

Energy Saving Trust, 2008. DRIVEN: A review of the passenger car market in the UK through history to the present. Energy Saving Trust, London.

Enkvist, P.-A., Nauclér, T., Rosander, J., 2007. A cost curve for greenhouse gas reduction, The McKinsey Quarterly, No.1. McKinsey & Company, San Francisco, USA.

Fulton, L., Cazzola, P., Cuenot, F., 2009. IEA Mobility Model (MoMo) and its use in the ETP 2008. Energy Policy 37, 3758-3768.

Georgakaki, A., Coffey, R.A., Lock, G., Sorenson, S.C., 2005. Transport and Environment Database System (TRENDS): Maritime air pollutant emission modelling. Atmospheric Environment 39, 2357-2365.

Goodwin, P., Dargay, J., Hanly, M., 2004. Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income: A Review. Transp. Rev. 24, 275-292.

Hickman, J., Hassel, D., Joumard, R., Samaras, Z., Sorenson, S., 1999. MEET - Methodology for calculating transport emissions and energy consumption, TRL report No. PR/SE/491/98. TRL, Crowthorne.

Hickman, R., Banister, D., 2007. Looking over the horizon: Transport and reduced CO2 emissions in the UK by 2030. Transport Policy 14, 377-387.

HM Treasury, 2006. The Stern Review: The Economics of Climate Change. The Stationary Office, London.

HM Treasury, 2008. Pre-Budget Report 2008: Facing global challenges: supporting people through difficult times, Cm 7484. The Stationery Office, London.

Höpfner, U., Knörr, W., Ciroth, A., 2007. Datenprojekt Transport, Projektbericht. Netzwerk Lebenszyklusdaten (German Network on Life Cycle Inventory Data), Forschungszentrum Karlsruhe, Karlsruhe.

ICO, 2006. ISO 14040: Environmental management - Life cycle assessment - Principles and framework. International Organisation for Standardisation (ISO), Geneva.

IEA, 2008. Energy Technology Perspectives. International Energy Agency (IEA), Paris, France.

INFRAS, 2004. Handbook emission factors for road transport (HBEFA), version 2.1. INFRAS, Bern (CH).

Inman, M., 2008. Carbon is forever, News Feature, Nature Reports Climate Change. Nature, published online: 20 November 2008 | doi:10.1038/climate.2008.122.

International Iron and Steel Institute, 2002. World Steel Life Cycle Inventory, Methodology Report. International Iron and Steel Institute, Committee on Enironmental Affairs, Brussels.

IPCC, 2007. Summary for Policymakers, in: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge.

ITS Leeds, 2001. Updating Car Ownership Forecasts, Final Report to the then Department of the Environment, Transport and the Regions. Institute for Transport Studies, Leeds.

IWW, ME&P, INRETS, CSST, DLR, EPFL, ISIS, ITS, KTI, LT Consultants Ltd., Marcial Echenique y Compaña, NEA, NTUA, TIS, TNO Inro, TRT, UG, UPM, 2000. SCENES European Transport Forecasting Model and Appended Module: Technical Description, Deliverable D4 of the SCENES project funded by the European Commission, DG VII, last accessed on 12/04/2005 at http://www.iww.uni-karlsruhe.de/SCENES. European Commission, Brussels.

Jackson, J., Choudrie, S., Thistlethwaite, G., Passant, N., Murrells, T.P., Watterson, J.D., Mobbs, D.C., Cardenas, L., Thomson, A., Leech, A., 2009. UK Greenhouse Gas Inventory: 1990 to 2007, Annual Report for Submission under the Framework Convention on Climate Change. AEA Technology, Harwell.

Joint Research Centre, 2006. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, Well-to-Wheels Report, version 2c, March 2007 (last accessed at http://ies.jrc.ec.europa.eu/WTW on 19/03/09). Joint Research Centre of the European Commission (JRC), The oil companies' European association for environment, health and safety in refining and distribution (CONCAWE) and European Council for Automotive Research and Development (EUCAR), Ispra, Italy.

Kollamthodi, S., Brannigan, C., Harfoot, M., Skinner, I., Whall, C., Lavric, L., Noden, R., Lee, D., Buhaug, Ø., Martinussen, K., Skejic, R., Valberg, I., Brembo, J.C., Eyring, V., Faber, J., 2008. Greenhouse gas emissions from shipping: trends, projections and abatement potential, final report to the Committee on Climate Change. AEA Energy & Environment, Harwell.

Lane, B., 2006. Life Cycle Assessment of Vehicle Fuels and Technologies, Final Report including Appendices. Ecolane Transport Consultancy, Bristol.

Loulou, R., Goldstein, G., Noble, K., 2004. Documentation for the MARKAL family of models, http://www.etsap.org/. Energy Technology Systems Analysis Programme (ETSAP), an Implementing Agreement of the International Energy Agency (IEA), Paris.

MacLean, H.L., Lave, L.B., 2003. Life Cycle Assessment of Automobile/Fuel Options. Environ. Sci. Technol. 37, 5445–5452.

Marheineke, T., Friedrich, R., Krewitt, W., 1998. Application of a Hybrid Approach to the Life Cycle Inventory Analysis of a Freight Transport Task, SAE Technical Paper Series 982201. Society of Automotive Engineers (SAE), Warrendale, PA.

Martino, A., Schade, W., 2000. The ASTRA Platform for the Strategic Assessment of European Transport Policies, Paper presented at the THINK UP Workshop 5, Setting the Policy Context, Vienna.

Nemuth, S., Kreißig, J., 2007. Datenprojekt Zement im Netzwerk Lebenszyklusdaten, Projektbericht. Forschungszentrum Karlsruhe, Karlsruhe.

NETCEN, 2003. VEHICLE SPEED EMISSION FACTORS (Version 02/3), http://www.naei.org.uk/other/vehicle_emissions_v8.xls, last accessed on 20/10/2005. NETCEN, AEA Technology plc for DEFRA, Harwell.

ONS, 2008. Population Trends No 132, Summer 2008, Office for National Statistics (ONS). Palgrave Macmillan, Basingstoke.

RFA, 2008. The Gallagher Review of the indirect effects of biofuels production. Renewable Fuels Agency (RFA), St Leonards-on-Sea.

Schäfer, A., Heywood, J.B., Weiss, M.A., 2006. Future fuel cell and internal combustion engine automobile technologies: A 25-year life cycle and fleet impact assessment. Energy 31, 2064-2087.

Schäfer, A., Jacoby, H.D., 2006. Vehicle technology under CO2 constraint: a general equilibrium analysis. Energy Policy 34, 975-985.

SMMT, 2008. New car CO2 report 2008: driving down emissions. The Society of Motor Manufacturers and Traders (SMMT), London.

SMMT, 2009. Motor Industry Facts 2009. Society of Motor Manufacturers and Traders (SMMT), London.

Strømman, A.H., Peters, G.P., Hertwich, E.G., 2009. Approaches to correct for double counting in tiered hybrid life cycle inventories. Journal of Cleaner Production 17, 248-254.

Syri, S., Amann, M., Capros, P., Mantzos, L., Cofala, J., Klimont, Z., 2001. Low-CO2 energy pathways and regional air pollution in Europe. Energy Policy 29, 871-884.

Train, K., 2009. Discrete Choice Methods with Simulation, 2nd ed. Cambridge University Press, Cambridge.

UK Energy Research Centre, 2009. Making the transition to a secure and low-carbon energy system: synthesis report. UK Energy Research Centre, London.

Whelan, G., 2007. Modelling car ownership in Great Britain. Transportation Research Part A: Policy and Practice 41, 205-219.

Wohlgemuth, N., 1997. World transport energy demand modelling : Methodology and elasticities. Energy Policy 25, 1109-1119.

Zachariadis, T., 2005. Assessing policies towards sustainable transport in Europe: an integrated model. Energy Policy 33, 1509-1525.

Zachariadis, T., Samaras, Z., Zierock, K.-H., 1995. Dynamic Modeling of Vehicle Populations: An Engineering Approach for Emissions Calculations. Technological Forecasting and Social Change 50, 135-149.

Zamel, N., Li, X., 2006. Life cycle analysis of vehicles powered by a fuel cell and by internal combustion engine for Canada. Journal of Power Sources 155, 297-310.