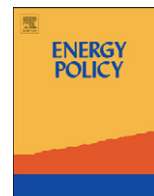




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Modelling transport energy demand: A socio-technical approach

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ABSTRACT

Despite an emerging consensus that societal energy consumption and related emissions are not only influenced by technical efficiency but also by lifestyles and socio-cultural factors, few attempts have been made to operationalise these insights in models of energy demand. This paper addresses that gap by presenting a scenario exercise using an integrated suite of sectoral and whole systems models to explore potential energy pathways in the UK transport sector. Techno-economic driven scenarios are contrasted with one in which social change is strongly influenced by concerns about energy use, the environment and well-being. The 'what if' Lifestyle scenario reveals a future in which distance travelled by car is reduced by 74% by 2050 and final energy demand from transport is halved compared to the reference case. Despite the more rapid uptake of electric vehicles and the larger share of electricity in final energy demand, it shows a future where electricity decarbonisation could be delayed. The paper illustrates the key trade-off between the more aggressive pursuit of purely technological fixes and demand reduction in the transport sector and concludes there are strong arguments for pursuing both demand and supply side solutions in the pursuit of emissions reduction and energy security.

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1. Introduction

Despite a widely agreed consensus that societal energy consumption and related emissions are not only influenced by technical efficiency but also by lifestyles and socio-cultural factors (e.g. household size and composition, expenditure patterns, social norms, habits and the ageing population), there is a methodological gap between the perceived importance of these factors for energy demand and quantitative modelling frameworks or even scenario analysis. Indeed, there is much less consensus as to the character and extent of these influences, particularly when broadened out from societal changes to include individual psycho-social factors such as well-being, social norms and values. In particular, very few attempts have been made to operationalise these insights into models of future energy demand.

This paper addresses this gap in research and practice by presenting a quantitative scenario exercise using an integrated suite of sectoral and whole systems models to explore potential energy pathways in the UK transport sector. Presenting results in part from the UK Energy Research Centre's Energy 2050 project (Skea and

Ekins, 2009), techno-economic driven scenarios are contrasted with one in which social change is strongly influenced by concerns about energy use, the environment and well-being so that transport energy service demand is at a significantly lower level by 2050 than in the 'business as usual' assumptions of other pathways.

Empirical evidence of the potential for travel patterns to change incrementally in response to policy and normative shifts was combined with the development of a plausible 'what if' qualitative storyline about attitudinal, cultural and behavioural change to 2050. The associated transport energy service demands were modelled using MARKAL elastic demand (MED) to assess the implications on fuel demand, emissions and the wider energy sector in the UK. This involved the novel intermediate step of soft-linking MED with a newly developed strategic transport, energy, emissions and environmental impacts model—the UK transport carbon model (UKTCM) (see Brand et al., this issue). UKTCM is a highly disaggregated, bottom-up model of transport energy use in the UK. It allows us to model the energy service demands and vehicle choice of different assumptions about transport service demand, modal choice and trip patterns.

This paper demonstrates how sectoral and energy system models can be soft-linked to explore future scenarios in which the potential contribution of demand-side behaviour change is explored alongside technological change to meet a stringent 80% emissions reduction target in the UK.

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2. Background

At the global level, transport currently accounts for more than half the oil used and nearly 25% of energy related carbon dioxide (CO₂) emissions (IEA, 2008). From a 2005 baseline, transport energy use and related CO₂ emissions are expected to increase by more than 50% by 2030 and more than double by 2050 with the fastest growth from light-duty vehicles (i.e. passenger cars, small vans, sport utility and vehicles), air travel and road freight (IEA, 2008).

Transport is invariably deemed to be the most difficult and expensive sector in which to 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. The conventional transport policy response to this issue reflects this dominant technoeconomic analytical paradigm and focuses on supply-side vehicle technology efficiency gains and fuel switching as the central mitigation pathway for the sector. Typically, the diffusion of advanced vehicle technologies is perceived as the central means to decarbonise transport. Since many of these technologies are not yet commercially mature, or require major infrastructure investment, this focus has reinforced the notion that the transport sector can only make a limited contribution to total CO₂ emissions reduction, particularly in the short term (HM Treasury, 2006; Koehler, 2009). In the UK for example, electrification of the passenger vehicle fleet is a key strategy and viewed as necessary to achieve the government's stated 2050 target to cut CO₂ equivalent of Kyoto GHG emissions by 80% from 1990 levels (Ekins et al., 2009; CCC, 2009). The UK policy focus on vehicle technology reflects other global transport modelling exercises that depend upon between 40% and 90% market penetrations of technologies such as plug-in hybrids and full battery electric vehicles between 2030 and 2050 (IEA, 2008; McKinsey and Company, 2009; WBCSD, 2004; WEC, 2007).

Although scenario exercises such as these are used to explore the potential CO₂ emissions reduction from rapid uptake of vehicle technologies, the central danger is that the full potential and necessary contribution of human behaviour, lifestyle change and the important role of individual attitudes and perceptions are often overlooked by policy makers. Other than changes in preference required to facilitate the uptake of low carbon vehicles, many of these scenario exercises treat other societal developments of significance to transport as external to policy. In addition, where societal developments are included, individual behaviour change is invariably treated in abstract terms as part of broader societal changes (Weber and Perrels, 2000).

An alternative would be to conduct scenario planning exercises which underline the role that policy can play in working with attitudes, opportunities and impacts to exert positive influence on the type of society that is developing and the nature of the transport system that thus co-evolves with it (Marsden et al., 2010). In particular, such approaches pay attention to the interaction between society and technology (Elzen et al., 2002). The lifestyle approach is usually juxtaposed from one with a purely technological focus as it tries to provide a wider picture of the consumer (and required production processes to satisfy his needs and wants) by depicting him or her in his socio-economic context (Baiocchi et al., 2006). Individual attitudes and values are seen as influential in shaping society's engagement with technological opportunities in the face of environmental impacts that will likely force a direction of response from policy makers and society.

To support this approach, there is a growing evidence base, or even just a renewed appreciation of existing evidence, of the potential for behaviour to alter in ways which mean that reductions in the demand for travel activity and associated energy are both plausible and cost effective (Sloman et al., 2010; Cairns et al., 2008; Goodwin, 2008. Also see Gross et al. (2009) for a comprehensive overview of the literature). These behaviour changes encompass a whole variety of different types of choice related to travel demand which include much more than simply 'retrofitting' more efficient transport modes on to current journey patterns. In other words, a reduction in energy service demand from transport will be achieved through a myriad of individual and societal level shifts in preference for the amount of time travelling, the choice of destinations and where to live, attitudes towards health and the environment and the local community, different models of car ownership, driving behaviour as well as more 'standard' decisions about mode and car choice. The 'Lifestyle' storyline of the Energy 2050 project looks at all of these travel behavioural choices and speculates about the nature and extent of plausible shifts before using an integrated modelling framework to examine the implications for the UK energy system and carbon reduction targets.

3. Methodology

The UKERC Energy 2050 project aimed to show how the UK can move towards a resilient and low carbon energy system over the period to 2050 (Skea and Ekins, 2009). The project focuses on two primary goals of UK energy policy—achieving deep cuts in CO₂ emissions by 2050, taking the current UK 80% reduction goal as a starting point, and developing a 'resilient' energy system that ensures consumers' energy service needs are met reliably. In addition, other policy goals are taken into account, namely managing environmental impacts other than those related to climate change and ensuring that everyone has access to affordable energy services.

The core analysis used a combination of sectoral and 'whole systems' models of the UK energy system to investigate key uncertainties in low and carbon resilient energy through a systematic comparison of scenarios. The system level models captured interrelationships and choices across the energy system and consisted of MARKAL (MARKet Allocation), a widely applied bottom-up, dynamic, linear programming optimisation model (Loulou et al., 2004), and an elastic demand version (MARKAL elastic demand (MED)). MED is a technology-rich, multi-time period optimisation model and portrays the entire energy system from imports and domestic production of fuel sources through to fuel processing and supply, explicit representation of infrastructures, conversion of fuels to secondary energy carriers (including electricity, heat and hydrogen), end use technologies and energy service demands of the entire economy. The model accounts for the response of energy service demands (ESDs) to prices which, in this exercise, could themselves increase as a result of carbon constraints (Anandarajah et al., 2008).

In the 'Lifestyles' sub-project of Energy 2050, two out of the four core scenarios developed in Energy 2050 were used as a starting point to be contrasted with two Lifestyle 'variants' of these core scenarios (hereafter referred to as the 'Lifestyle variants'). Before Lifestyle variants could be run in MED, an alternative set of direct inputs in the form of energy service demands, vehicle load factors, downsizing of the car fleet, low carbon technology take-up and changes in on-road fuel efficiencies needed to be generated. This was undertaken for both the residential and the transport sectors but this paper concentrates on the development of the transport inputs only (see Anable et al.

(2010) for a detailed overview of the methodology). The modelling of mobility energy demands for these variants involved:

1. Framing and development of a new 'Lifestyle' storyline and translating this, using spreadsheet modelling, into projections of travel patterns as an alternative to official UK government projections used in the core Energy 2050 scenarios.
2. Detailed sectoral modelling using the newly developed UK transport carbon model (UKTCM) in order to simulate the impacts of lifestyle changes on vehicle ownership, vehicle technology choice and vehicle use.
3. Soft-linking of UKTCM and MED by aggregating and converting UKTCM outputs into MED inputs before MED was run.

Each of these stages will now be described in turn.

3.1. The lifestyle storyline and spreadsheet modelling

Transport energy demand is a function of mode, technology and fuel choice, total distance travelled, driving style and vehicle occupancy. Distance travelled is itself a function of land use patterns, destination, route choice and trip frequency. Most travel behaviour modelling and forecasting is based on principles of utility maximisation of discrete choices and on the principle that travel-time budgets are fixed (Metz, 2002). However, based on the literature on socio-technical transitions, socio-psychological models of behaviour change and evidence relating to actual travel choices in response to policy interventions as well as, the Lifestyle variant explored a world in which travel behaviour is strongly influenced by concerns relating to health, quality of life, energy use and environmental implications. As such, non-price driven behaviour, which has already been found to play a significant role in transport choices (Anable, 2005; Steg, 2004; Turrentine and Kurani, 2007) was deemed to be a dominant driver of energy service demand from transport. It should be noted that this paper does not review the literature pertaining to behaviour change theory and the detailed combination of ingredients (motivational and external) required for travel patterns to shift dramatically, nor does it review the policy evidence in detail. We refer readers to Anable et al. (2010) for the detail behind the Lifestyle storyline.

Making assumptions in this way, albeit based on uncertain evidence, is akin to the treatment of the technical potential of various solutions relating to vehicle technologies and fuels which, as discussed, normally comprise the bulk of the future developments in transport energy scenario modelling exercises, despite also being highly uncertain. In judging what rate and scale of change seems plausible we have given most weight to the existing variation in lifestyle observed in societies like our own, i.e. technologically advanced, liberal democracies. Subject to some obvious constraints imposed by age, wealth and location, for example, it seems reasonable to suppose that if a significant fraction of the population (say 5–10%) somewhere in the OECD already behave in a particular way, then it is plausible for this to become a majority behaviour in the UK within the timeframe to 2050. This implies neither incremental nor step changes in behaviour. There are increasing suggestions that incremental changes in efficiency and behaviour will not be effective enough to deliver sustainable energy systems on their own in the absence of restrictions in consumption (Darby, 2007; Crompton, 2008). In addition to incremental change, there is considerable interest in the possibility of a 'cultural shift' affecting people's lifestyles (Elzen et al., 2002; Evans and Jackson, 2007; Koehler, 2009; Crompton, 2008). Consequently, this Lifestyle variant outlines

radical change leading to relatively fast transformations and new demand trajectories.

In the Lifestyle variant, travellers are more aware of the whole cost of travel and the energy and emissions implications of travel choices and are sensitive to the rapid normative shifts which alter the bounds of socially acceptable behaviour. Consequently, the variant assumed the focus would shift away from mobility towards accessibility. In other words, the quality of the journey experience rather than the quantity and speed of travel would become more important. Social norms elevate active modes and low-carbon vehicles in status and demote large cars, single-occupancy car travel, speeding and air travel.

Efficient, low-energy and zero energy (non-motorised) transport systems will replace current petrol and diesel car-based systems. The increased uptake of slower, active modes reduces average distances travelled as distance horizons change. Localism means people work, shop and relax closer to home and long-distance travel will move from fast modes (primarily air and the car) to slow-speed modes covering shorter distances overall (local rail and walking and cycling). The novelty of air travel wanes as not only does it become socially unacceptable to fly short distances, airport capacity constraints mean it becomes less convenient. Weekends abroad are replaced by more domestic leisure travel but this is increasingly carried out by low-carbon hired vehicles, rail and luxury coach and walking and cycling trips closer to home. It also becomes socially unacceptable to drive children to school. However, capacity constraints limit the pace of change so that mode shift to buses and rail will be moderated. New models of car ownership are embraced. This includes car clubs² and the tendency to own smaller vehicles for every day family use and to hire vehicles for longer distance travel. These are niche markets in which new technology is fostered. Lower car ownership is correlated with lower car use.

The new modes, in turn, will result in a new spatial order towards compact cities, mixed land uses and self contained cities and regions. Some services return to rural areas, but it becomes more common to carry out personal business by internet. Small-scale technology facilitates relatively rapid behavioural change. Information and Communication Technology (ICT: telematics, in-car instrumentation, video conferencing, smartcards and e-commerce) makes cost and energy use transparent to users and changes everything from destination choice, car choice, driving style and paying for travel, including in the freight sector. A more radical change takes place through changes in work patterns and business travel. The impacts of teleworking and video conferencing are known to be complex, but potentially important (Gross et al., 2009). Teleworking particularly affects the longer commute trips and thus has a disproportionately large impact on average trip lengths. Increased internet shopping and restrictions on heavy goods vehicles, particularly in town centres, increases the use of vans. There is some shift towards rail freight.

There is increasing acceptance of restrictive policies in the context of more choice for local travel as the alternatives are improved. These restrictions include the general phasing out of petrol/diesel vehicles in town/city centres through low emission zones, increased parking charges and strict speed enforcement. Generally, however, the policy environment is one of 'push and pull' as fiscal and regulatory sticks are combined with the carrot of infrastructure investment (e.g. in car clubs, public transport, cycle infrastructure and railway capacity).

Combined with the shifts towards active modes and different models of car ownership, this amounts to significant lifestyle

² In the UK, Car clubs are 'pay as you go' car hire schemes known as 'Car sharing' in many other European Countries.

shift. The consequences for travel patterns of these shifts were first analysed using a spreadsheet model which took as its starting point the figures for individual travel patterns in 2007 based on the UK National Travel Survey (DfT, 2008). Figures for each journey purpose (commuting, travel in the course of work, shopping, education, local leisure, distance leisure and other) in terms of average number of trips, average distance (together producing average journey length), mode share and average occupancy were altered based on an evidence review relating to the impact of transport policies and current variation in travel patterns within and outside the UK (see Anable et al. (2010) for a detailed overview of the calculations).

The underlying principle of the derived projections of 'lifestyle' travel patterns is that they should be internally consistent and plausible. The method of how they were derived implies that they do not present a forecast using an econometric transport demand model, or a 4-stage transport demand network model. Specifically, the lifestyle projections of travel demand are not the result of changes in income or price elasticities of demand, GDP or population growth. The derived 'Lifestyle' travel demand projections actually imply gradually lower income (and population) elasticities of demand as incomes and population continue to grow in all four scenarios considered in this paper (see Table 1). Notably, in order to avoid double counting once these projections

Table 1
Summary of the four contrasting scenario runs using MED.

	Core energy 2050 scenarios		Lifestyle variants of the core energy 2050 Scenarios	
	REF	Low carbon REF (LC)	Lifestyle REF (LS REF)	Lifestyle low carbon (LS LC)
Key assumptions	Provides a baseline from which to assess the actions and costs associated with achieving policy goals. Concrete policies and measures in place in the UK in 2007 continue into the future but no additional measures are introduced	REF+carbon constraint leading to an 80% reduction in UK carbon emissions by 2050 relative to 1990, with an intermediate milestone of 26% in 2020 and linear interpolation in between	Shifts in societal preferences, activities and associated policies generate alternative energy service demands, vehicle technology uptake and on-road fuel efficiencies. MED was run without a carbon constraint akin to the core REF scenario	LS REF+carbon constraint leading to an 80% reduction in UK carbon emissions by 2050 relative to 1990, with an intermediate milestone of 26% in 2020 and linear interpolation in between
Method	UK Government projections+MED	UK Government projections+MED	UK Government projections+spreadsheet+UKTCM+MED	UK Government projections+spreadsheet+UKTCM+MED
GDP and population growth	Historic long-term average GDP growth rate for the UK of 2.0% continues to 2050; projections of population growth were taken from UK Government sources			
Lifestyle assumptions	Lifestyle choices continue to develop along the same trajectory as in the past—i.e. there will be a greater take-up of energy efficiency measures, but people are assumed to balance the initial cost of efficiency measures against on-going energy costs (based on observed income elasticities of demand) with increasing wealth at the projected growth rate	Lifestyle choices are strongly influenced by concerns about energy use, the environment and well-being. Not only are non-price determinants of behaviour recognised, such as values, norms, fashion, identity, trust and knowledge, but also non-consumptive elements of behaviour such as patterns of time use, mobility, social networking, expectations and policy acceptance. Policy shifts will empower consumers to change lifestyles and to loosen some of the external constraints that make changes towards more sustainable travel patterns difficult		
Demand elasticities	MED demand elasticities remain unchanged over time to reflect the fact that energy consumer preferences (i.e. the way they respond to prices and available technology) stay the same	The derived 'lifestyle' travel demand projections imply gradually lower elasticities of demand as incomes and population continue to grow. In order to avoid double counting the transport (and residential energy) demand elasticities in the Lifestyle MED runs were set to zero (while agriculture, service and industry demand elasticities were untouched)		

Note: These 4 scenarios should not be confused with the two model runs produced separately in UKTCM (TCM REF and TCM LS) as an intermediate stage in the methodology (see Section 3.2).

were eventually fed into MED, the transport demand elasticities in the Lifestyle MED runs were set to zero.

3.2. Modelling lifestyle using the UK transport carbon model

The UKTCM is a strategic transport-energy-environment simulation model designed to model a wide range of policies and policy ‘packages’ (or ‘bundles’) including demand management policies, measures affecting vehicle ownership and use, fiscal and pricing policies, eco-driving programmes, fuel obligations, speed enforcement and targeted technology investment incentives. It provides annual projections of transport supply and demand, and calculates the corresponding energy use, lifecycle emissions and environmental impacts year-by-year up to 2050. It simulates passenger and freight transport across all transport modes, built around exogenous scenarios of socio-economic and political developments. It integrates simulation and forecasting models of elastic demand, vehicle ownership, technology choice (using a discrete choice modelling framework), stock turnover, energy use and emissions, lifecycle inventory and impacts, and valuation of external costs. An introduction to the model has been published in Brand et al. (this issue); further details can be obtained from the Reference Guide (Brand, 2010a) and User Guide (Brand, 2010b), published by the UK Energy Research Centre.

The set of ‘Lifestyle’ transport energy serviced demands (distance travelled, mode split and vehicle occupancy) developed above was entered into UKTCM as exogenous transport demands. In addition, lower multiple car ownership was simulated by lowering the car ownership saturation levels for households owning 2 or more cars. It was further assumed that by 2020 no ‘large cars’ (above a certain engine size and gross vehicle weight) are being sold. The changes in social norms, consumer preferences, improved performance and market presence of low carbon road vehicles (essentially efficient hybrid electric vehicles (HEV), battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV)) were modelled by assuming low carbon road vehicles have gradually increasing consumer preferences, performance and market availability up to the point where they are comparable (or even better) than their conventional counterparts of a certain reference technology (e.g. medium size gasoline internal combustion engine car of vintage 2015–2019). The scale and timing of these changes have been modelled on the assumptions behind the high- to extreme-range technology scenarios of the recent scoping exercise commissioned by UK Government Departments (BERR & DfT, 2008), and further informed by low carbon transport scenario work such as reported in Hickman and Banister (2007). Within the UKTCM discrete choice modelling framework, equal preference implies equality in perceived market potentials (availability of infrastructure), perceived risk (fuel type, ‘proven’ vs. ‘new’ technology) and performance (range, speed, acceleration, etc.). No changes in investment and fixed Operation and Management (O&M) costs were assumed, as consumers of tomorrow choose to buy greener vehicles not on the basis of reduced purchase prices but on the basis of changed preferences for and perceived risk of a low-carbon vehicle. Finally, the on-road fuel efficiency programme and general adherence to speed limits was modelled by assuming an alternative set of speed profiles for motorways and dual carriageways, with direct effects on on-road fuel consumption.

In the results sections below, the UKTCM Lifestyle outputs (TCM LS) are contrasted to a reference case (TCM REF). These two model runs represented an intermediate stage in the methodology and are not to be confused with the MED scenarios outlined in Table 1 which ultimately generated the system level energy demands and progress towards UK carbon emissions targets.

3.3. MARKAL elastic demand

UKTCM outputs (fuel consumption, vehicle fleet evolution by vehicle technology) were translated into MED inputs (technical energy efficiency, technology deployment constraints and bounds).

MED was then run to produce four contrasting scenarios—two core Energy 2050 scenarios and two Lifestyle ‘variants’. In each case, they were distinguished by whether they were unconstrained (REF) or constrained³ (LC) to guarantee the achievement of an 80% fall in UK carbon emissions relative to 1990 levels by 2050. Thus, four scenarios resulted as follows:

- REF: unconstrained core Energy 2050 Reference Scenario.
- LC: constrained low carbon core Energy 2050 Scenario.
- LS REF: unconstrained Lifestyle variant.
- LS LC: constrained low carbon Lifestyle variant.

The detailed assumptions embedded in the core scenarios are available in Skea and Ekins (2009). Table 1 provides an overview of the key elements of each.

The following 3 sections outline the results relating to the impacts on: travel patterns and vehicle technology, energy use and fuel demand in the transport sector and carbon emissions and the wider energy system.

4. Impact on travel patterns and vehicle technology

The impact on travel patterns was modelled using the spreadsheet model and UKTCM as described above and the results can be divided into the following key areas of energy service demands from transport:

- Changing surface passenger travel patterns.
- Domestic air travel and surface freight transport.
- Driving style and on-road fuel efficiency.
- Vehicle ownership and technology choice.

4.1. Changing surface passenger travel patterns

Based on the initial spreadsheet modelling exercise which altered average number of trips, total distance, mode share and vehicle occupancy for each journey purpose, this first exercise resulted in a 74% reduction in distance travelled by car by 2050 as a driver and a passenger. The use of all other surface transport modes increases, apart from a 12% fall in distance travelled by Heavy Goods Vehicles (HGV or trucks). The reduction in car travel comes about as a result of significant mode shifts, particularly to bus travel towards the latter half of the period (184% increase in vehicle kilometres) and cycling and walking. Mode shift is combined with a fall in average trip lengths due to destination shifting as a result of localisation and a fall in the total number of trips per capita as some journeys are replaced with ‘virtual’ means.

Fig. 1 shows how people become progressively more ‘multi-modal’ by the end of the period in the LS REF variant. In 2020, the car is still used for the majority of distance travelled as a driver or passenger (67%), but this drops to 28% by 2050. However, ‘other

³ In the cases of the LC and LS LC scenarios, the carbon emissions constraint is binding before any system costs are optimised, resulting in higher overall system costs. The MED model provides marginal costs of reducing carbon emissions further than the constraint, thus providing a shadow price of carbon (as an output, not input).

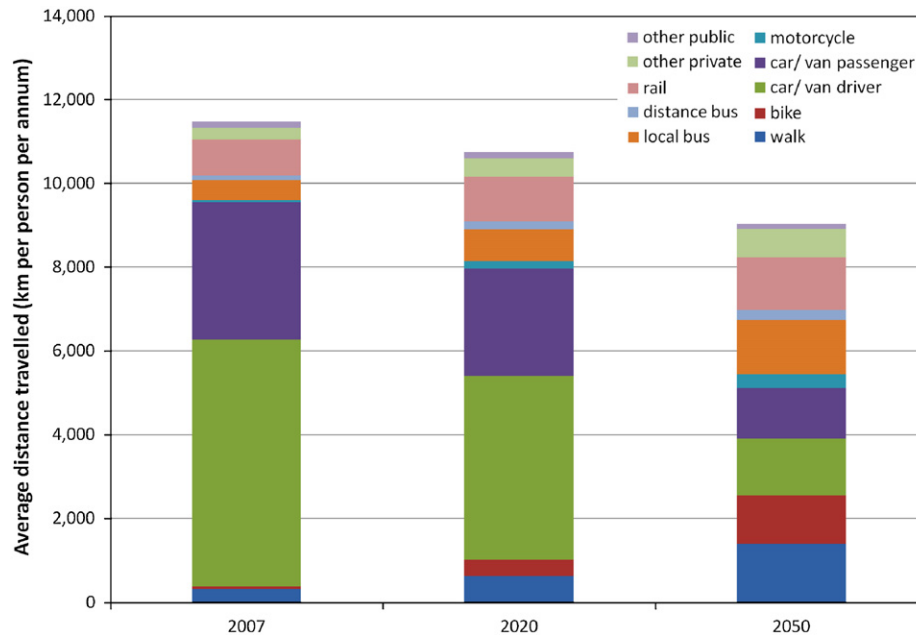


Fig. 1. Surface passenger transport by distance and mode split in different years in the LS REF and LS LC variants.

private' (which includes taxis, hire cars and car club cars) increases from 2.4% of distance in 2007, to 7.5% so that, combined with being a car passenger, 36% of all distance is still undertaken by car in 2050. At the same time, cycling goes from accounting for less than 1% to almost 13% of distance travelled. This surpasses levels seen today in countries regarded as demonstrating best practice in this area. For example, in 2006 an average Dutch person cycled 850 km/year, corresponding to around 8% of total distance travelled (SWOV, 2006). We chose to push this further over 40 years on the basis that the Dutch have achieved this level so far without comprehensively restricting cars from urban centres and increasing the cost of motoring, which our Lifestyle variant assumes. If cycling and walking are added together, 'active modes' account for 28% of travel in 2050. Implicit in the assumptions made here is the fact that cars are increasingly banned or priced out of city/town centres.

4.2. Domestic air travel and surface freight transport

With regard to air travel, growth in domestic flights are assumed to slow and eventually saturate. This is primarily due to three factors. Firstly, it becomes increasingly uncompetitive on the basis of cost as oil price increases and carbon taxation bring an end to budget airlines and cheap flights. Secondly, domestic flying also becomes uncompetitive in terms of time as rail is improved. Thirdly, flying becomes increasingly unacceptable, particularly for short distances, and thus returns to being a luxury activity. Average load factors in the LS REF and LS LC variants are assumed to stay unchanged compared to the REF and LC core scenarios. As a result, any changes in air passenger-km translate directly into air vehicle-km (domestic only). The resulting domestic air vehicle-km in the LS REF and LS LC variants are 2% and 16% lower in 2020 and 2050, respectively, than in the REF and LC core scenarios.

With regard to van traffic, van ownership and use continues to increase as it did in the decade prior to 2007, growing by 138% by 2050 over the 2005 levels. The move towards a service economy and more teleshopping contribute to this trend. As van technology improves and their cost of ownership and use declines, this further

encourages their use. Town/city centres increasingly ban heavy goods vehicles but allow electric vans and local traffic regulations will give priority to professional home delivery and coordinated urban distribution with clean vehicles. As a result, the overall distance travelled by vans increases by 5% by 2050 in the LS REF and LS LC variants when compared to the REF and LC core cases.

With regard to heavy goods vehicles, we assume their use is still set to grow (by 36% between 2005 and 2050) but as a result of increased load factors, overall distance travelled by these vehicles will fall by 3% (2020) and 12% (2050) in the LS REF and LS LC variants when compared to the REF and LC core scenarios. Changes in consumer demands (including through origin/ carbon labelling and dematerialisation (the substitution of products with services)) may lead to reductions in freight movements, but the greatest savings will come from more efficient logistics. The 'lorry intensity' of the UK economy (the ratio of lorry-kms to GDP) declined by almost 20% between 1990 and 2004, partly as a result of companies using vehicle capacity more efficiently (McKinnon, 2007). There, nevertheless, remains considerable potential for improving 'vehicle fill'. Companies can adopt a range of vehicle utilisation measures which would lead to reduced lorry-km and CO₂ emissions. In some cases this will require changes to current business practice utilising integrated logistic services pertaining to several steps of production and distribution and based on complex information systems. These changes will require policy support for the development of technologies and standards for automatic flexible freight handling and tracing together with the implementation of consolidation centres and the introduction of CO₂ related taxes for freight vehicles to effectively raise road transport costs (Hickman and Banister, 2007). These changes will together mean the growth in heavy freight will be substantially reduced, particularly by road. Rail and waterborne freight play a bigger role, mainly due to mode shift from roads.

4.3. Driving style and on-road fuel efficiency

Eco-driving reduces fuel consumption through more efficient driving style, reducing speeds, proper engine maintenance,

maintaining optimal tyre pressure, and reducing unnecessary loads (King, 2007; TNO, 2006). Policy measures can include information campaigns and encouraging or requiring driver training. Potential savings appear to be significant and costs low, with the biggest obstacles being securing driver participation and ensuring that efficient driving habits are sustained over time (Gross et al., 2009). This suggests that if the potential benefits of more efficient driving styles are to be secured, an ongoing programme of training, and reinforcement through advertising and other awareness raising mechanisms is likely to be needed.

In the Lifestyle variants, the high cost of motoring and the social pressure to improve driving standards for both safety and environmental reasons, mean that efficiency, quality and reliability overtake speed as the priority for travel. Speeding becomes socially unacceptable as it is seen as wasteful. Eco-driving is reinforced with strict speed enforcement, high penalties and tax incentives for in-car instrumentation such as speed limiters, fuel economy meters and tyre pressure indicators.

Initial calculations were made in the spreadsheet model by assuming how many drivers in any given year would be practicing eco-driving and what proportion of their miles would be affected at what level of efficiency improvement. In any given year, new drivers will start to practice these techniques, and for others the effectiveness will begin to 'trail off', although it is assumed that the behaviour is reinforced by repeat training programmes and campaigns so that it becomes more or less habitual. Even for those who are practicing it, not every mile they drive will be affected. For those miles affected, an 8% efficiency improvement is assumed. This is at the lower end of the evidence base (Gross et al., 2009). Business uptake of eco-driving is expected to be quicker as it is easier to integrate training programmes and instrumentation.

Eco-driving will also be practiced by van and truck drivers. Penetration through van fleet is expected to mirror that of car business travel. Penetration through the truck fleet is the same as for vans. However, the savings per mile are lower (4%) as these vehicles are already speed limited.

In each case (for cars, vans and trucks) the savings only apply to petrol/diesel vehicles. The potential to save fuel and emissions for alternative propulsion vehicles such as electric and plug-in hybrid electric vehicles is lower, as the propulsion system is already technically optimised, leaving less room for improvement by the driver (Gross et al., 2009). These assumptions were then combined to derive a time series of aggregate fuel consumption for the conventional car, van and truck fleets. This was then transferred to UKTCM by scaling the vehicle emissions factors used. For cars, for example, the vehicle distance (km) affected reaches 60% by about 2025. Multiplying this by 8% saving per km travelled gives 4.8% in fuel consumption and emissions savings, or a scaling factor of 0.952 applied to 'without eco-driving' fuel consumption and emissions. A summary of the effects of on-road fuel efficiency improvements from eco-driving is shown in Table 2.

4.4. Vehicle ownership and technology choice

In the LS REF and LS LC variants, private, fleet and commercial buyers prefer advanced conventional and electric vehicles over conventional internal combustion vehicles (ICV). The market responds by increasing availability and performance of lower carbon vehicles. This was first modelled in UKTCM before being translated into MED inputs and further modelling using MED.

Vehicle ownership and technology choice is modelled in much more detail in UKTCM than in MED; hence it is appropriate to present the intermediate results of vehicle technology choice by comparing UKTCM Lifestyle outputs (TCM LS) reference case

Table 2

On-road fuel efficiency improvements from ecodriving in the LS REF and LS LC variants.

	Vehicle distance (km) affected					
	2008	2010	2015	2020	2030	2050
Cars (%)	4	8	18	46	62	62
Vans (%)	4	8	18	50	70	70
Trucks (%)	4	8	18	50	70	70
Fleet average fuel efficiency and emissions improvements per km						
Cars ^a (%)	0.3	0.6	1.4	3.7	4.9	4.9
Vans ^a (%)	0.3	0.6	1.4	4.0	5.6	5.6
Trucks ^a (%)	0.2	0.3	0.7	2.0	2.8	2.8

^a Car and van drivers are assumed to be 8% more efficient per km, and HGV drivers 4% per km, due to eco-driving.

outputs (TCM REF).⁴ In the TCM LS model run, ultra efficient ICV and hybrid electric vehicle (HEV) are the main focus in the short term (up to 2020). Battery electric vehicles (BEV) fulfil market niche roles in the medium term (2015–2030), especially electric buses, cars and vans in urban areas. Plug-in hybrid electric vehicles (PHEV) dominate sales in the medium to long term (from 2025). This 'Lifestyle' purchasing behaviour is illustrated for cars in Fig. 2, showing historic and projected new car sales (not total fleet) by propulsion type for the TCM LS model run. While in 2007 more than 99% of new cars are conventional ICV, the TCM LS scenario suggests that by 2020 28% of new cars will be ultra-efficient HEV, 16% small BEV, and 8% PHEV. By 2050, nearly half (46%) of new cars will be PHEV, 18% HEV and 9% small BEV. Fig. 2 also illustrates the limited role of high-blend bio-fuels (mainly 100% second generation biodiesel) in the TCM LS model run, reflecting low consumer preference and limited market deployment due to sustainability and availability concerns.

Two further lifestyle changes were simulated for cars. First, car buyers – whether private, fleet or business – are assumed to choose smaller cars instead of larger ones. This is simulated in UKTCM by phasing out the sale of new large cars (engine size >2.0l) by 2020—starting in 2010, with linear interpolation between 2010 and 2020. Secondly, the tendency towards less overall car use and the increased membership of car clubs for use of a variety of types of cars for longer distance journeys is modelled endogenously in UKTCM by assuming significantly lower levels of maximum car ownership per household in urban and non-urban areas—about half of the reference value (TCM REF) for households owning 'at least 2 cars' and 'at least 3 cars'. The TCM REF levels are based on assumptions contained in the car ownership module of the UK government's National Transport Model (for details see ITS Leeds, 2001; Whelan, 2007), which imply a continued growth due to changes in income, household structure and license holding. By lowering the maximum levels for second, third or more cars per household we basically limit overall car ownership levels for multiple household car ownership.

The changes in overall traffic levels, modal shares and the increased demand for lower carbon vehicles modelled in UKTCM are further illustrated in Fig. 3, showing road vehicle traffic (in billion vehicle-km) in the UKTCM reference (TCM REF, on the left) and UKTCM Lifestyle (TCM LS, on the right) model runs. In TCM LS, total road vehicle-km stay about constant at current levels (while they nearly double in TCM REF), and conventional ICV technology

⁴ These two model runs represented an intermediate stage in the methodology and are not to be confused with the final MED-generated scenarios (the two core scenarios (REF and LC) and two variants (LS REF and LS LC)).

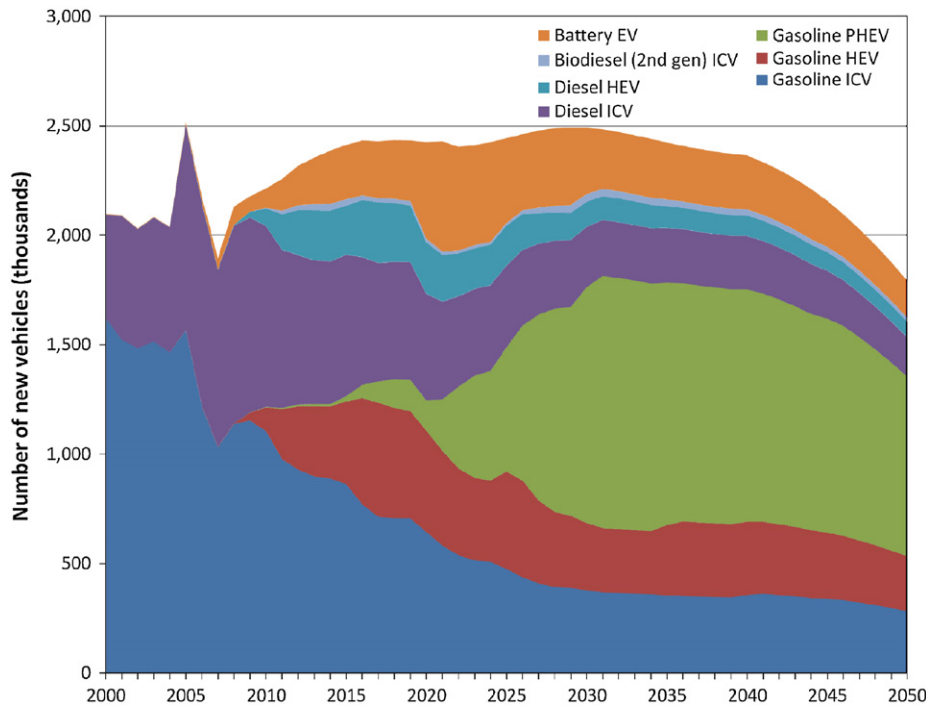


Fig. 2. New car sales by year as modelled by the TCM LS model run. ICV—internal combustion vehicle, HEV—hybrid electric vehicle, PHEV—plug-in hybrid electric vehicle, EV—electric vehicle, FCV—fuel cell vehicle, E85—85% bio-ethanol plus 15% petrol blend, biodiesel (2nd gen) and ICV—pure (100%) second generation biodiesel. The peak and subsequent drop in new car sales in 2005–2007 is based on observed data.

is gradually replaced by HEV, BEV and PHEV technology. While in 2007 less than 0.1% of car traffic is by cars other than conventional ICV, the TCM LS model run projects that by 2020 24% of car traffic will be ultra-efficient HEV, 7% small BEV, and 2% PHEV. By 2030, 27% of car traffic will be HEV, 22% PHEV and 13% small BEV. In the long term (2050), nearly half (45%) of car traffic will be PHEV, 20% HEV and 9% small BEV. Cars running on bio-fuels do not account for more than 2% of total car traffic over the period considered.

As for other vehicle types, the increase in motorcycle traffic is mainly for electric motorcycles. Penetrating the mass market from around 2012, 18% of truck vehicle-km will be HEV by 2020, increasing to 28% by 2040. PHEV trucks penetrate the market later and reach a plateau of about 22% roughly by 2035. BEV trucks never really take off, with BEV vans penetrating niches (about 3%) in the urban delivery market.

How does all this disaggregate modelling translate into MED inputs? The outputs of two UKTCM model runs (TCM REF and TCM LS) were aggregated (e.g. over car sizes), integrated with assumptions on car downsizing (see above) and translated into MED inputs for the Lifestyle variants (LS REF and LS LC) as energy service demands (in billion vehicle-km), average specific energy use figures (PJ/billion vehicle-km) for the MED vehicle types (NB: there is only one car size in MED). The inputs were essentially technology deployment bounds for minimum uptake and average vehicle fuel efficiencies (in combination with on-road fuel efficiency improvements). So as to avoid double counting, the transport demand elasticities in the Lifestyle MED runs were set to zero (while agriculture, service and industry demand elasticities were untouched) (see Table 1). In addition, the general shift in consumer preference was modelled in MED by assuming lower 'hurdle rates' (discount rate for capital expenditure) for energy-efficient and lower-carbon vehicles such as PHEV cars (12.5% instead of 15%, from 2020) and BEV motorcycles (15% instead of 25%, from 2015) when compared to the core REF scenario.

The final MED outputs show the significant variance in the traffic levels, modal shares and technology mixes between the

two core Energy 2050 scenarios and the two Lifestyle variants. Fig. 4 shows the car vehicle types in each of these 4 MED runs in 2020 and 2050. In the Lifestyle reference variants (LS REF & LS LC), by 2020 market shares (in terms of vehicle km, not energy use) for HEV and BEV cars reach 21% and 9%, respectively, compared to zero penetration in the core REF and LC scenarios. From 2020 gasoline PHEV cars become more popular in all but the core REF scenario, reaching market shares in 2050 of around 50%. In total, in the Lifestyle variants, HEV, BEV and PHEV cars have a 77–81% market share in 2050 albeit of a significantly smaller market overall (car use is 74% less than in the REF case). While diesel PHEV, hydrogen fuel-cell vehicles (FCV) and bio-methanol FCV cars do not appear in any of the scenarios, the core carbon constraint scenario (LC) sees a massive uptake of a high-level blend of bio-ethanol and petrol (E85) cars (33% of total car traffic in 2050), while the Lifestyle carbon constrained variant (LS LC) sees none. This suggests that at reduced demand levels in the Lifestyle variant, the shift to electric cars (BEV, PHEV) combined with a decarbonised electricity system is sufficiently cost-effective to avoid deployment of more costly bio-fuel technology.

The MED results suggest that in the unconstrained Lifestyle variant (LS REF) neither BEV nor PHEV road vehicles were taken up earlier or at higher levels than the rates laid down by UKTCM outputs. In contrast, HEV buses, trucks and vans were taken up at much higher levels (100% in some cases) when compared to the UKTCM outputs. This can be explained by lower annuitized cost for HEV than for their ICV counterparts and the use of only lower (no upper) limits for technology take-up as prescribed by the UKTCM outputs.

In all four scenarios modelled in MED, nearly all of van and HGV traffic in 2020 will be by ultra-efficient diesel/biodiesel HEV. This essentially means a complete hybridisation of the existing ICV road freight fleet over the next 10 years. By 2050, HGV traffic is still dominated by diesel/biodiesel HEV in the REF and LS REF runs, while in the carbon constrained runs (LC & LS LC) hydrogen fuel cell powertrains now dominate the HGV market. For vans,

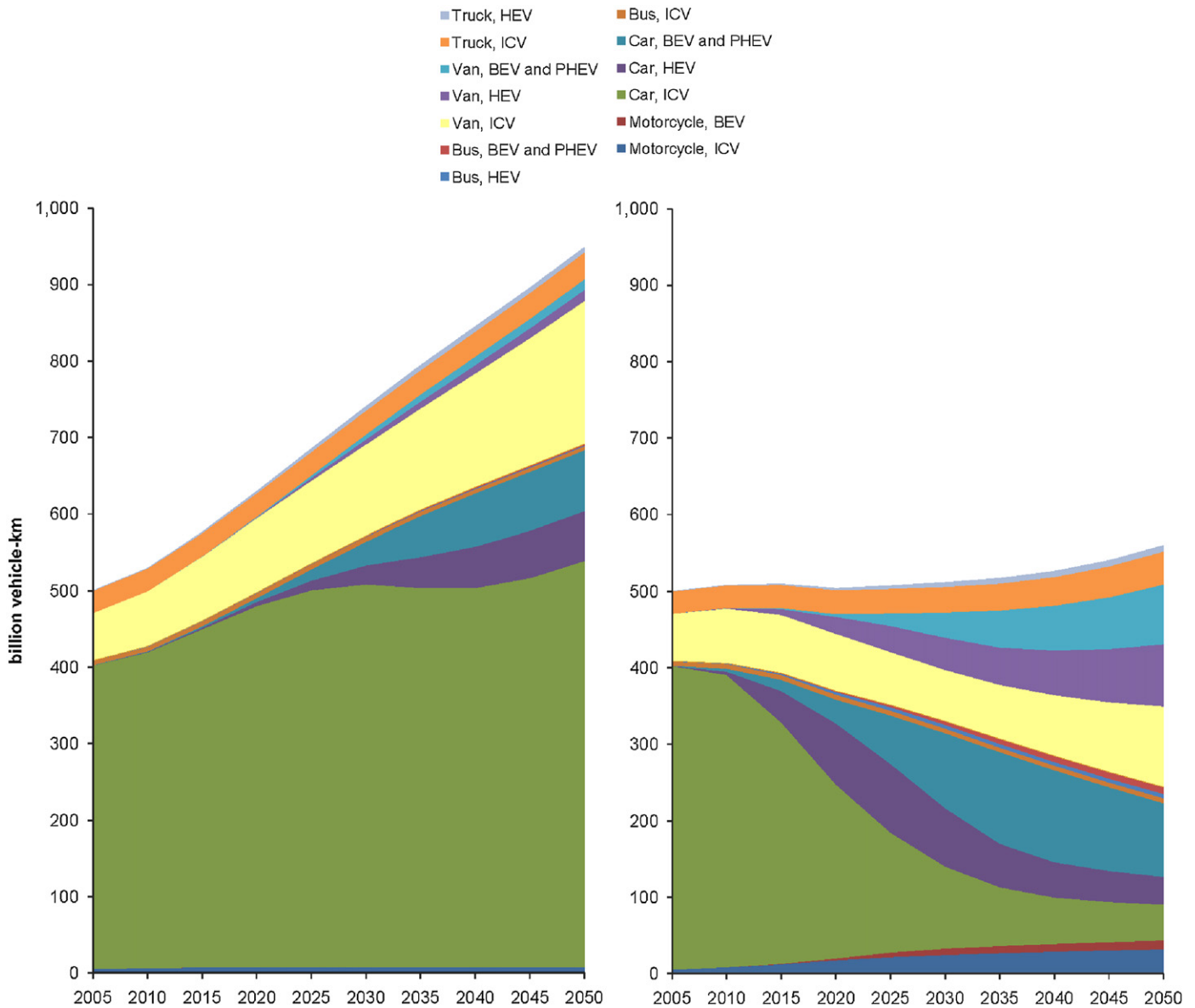


Fig. 3. UKTCM model run comparison for motorised road traffic by vehicle type and propulsion technology (TCM REF modelling run on the left, TCM LS on the right). ICV—internal combustion vehicle, HEV—hybrid electric vehicle, PHEV—plug-in hybrid electric vehicle and BEV—battery electric vehicle.

traffic in 2050 will be dominated by diesel/biodiesel HEV and gasoline PHEV in the carbon unconstrained runs (REF & LS REF). However, in the low carbon Lifestyle variant (LS LC), the market is more mixed as the carbon constraint results in higher take-up rates for biodiesel PHEV. BEV vans only appear in the Lifestyle variants as they penetrate niche markets in urban areas (7–8% of total road freight).

5. Impact on energy use and fuel demand in the transport sector

The higher uptake of lower and zero carbon vehicles combined with efficiency gains, downsizing of cars, mode shifts and significant alterations to work, shopping and leisure travel patterns result in final energy demand being halved from this sector in the unconstrained Lifestyle variant (LS REF) by 2050 compared to the unconstrained reference case (REF) (Fig. 5). In the unconstrained Lifestyle variant (LS REF), total fuel demand reduces by 23% by 2020 and by 43% by 2050 compared to the

2000 base. This contrasts to an increase of 15% in the reference case (REF) in 2050. The demand for conventional fuels (petrol+diesel) decreases by 57% by the year 2050 in the unconstrained Lifestyle variant (LS REF) and by 87% when constrained (LS LC). However, in all scenarios, conventional fuel still dominates use in 2020, never falling below 89% of total demand.

By comparison, electricity demand grows steeply, particularly in the second half of the period, accounting for 18% of total fuel demand in the unconstrained Lifestyle variants by 2050 (Fig. 5). This demand is 67% higher than in the unconstrained reference case (REF) where HEVs and BEVs have zero market share, even by 2050, although there is some increase in electricity use later in the period from rail, some battery operated buses and plug-in electric vans. In the constrained reference case (LC), however, the uptake of gasoline PHEVs is very high, although BEV uptake remains zero. Altogether, taking car (PHEV), vans (PHEV and BEV) and bus (BEV), a third of road transport energy demand is met by plug-in electric vehicle technology in 2050. Use of electrified rail also increases by over 200% over present use by 2050.

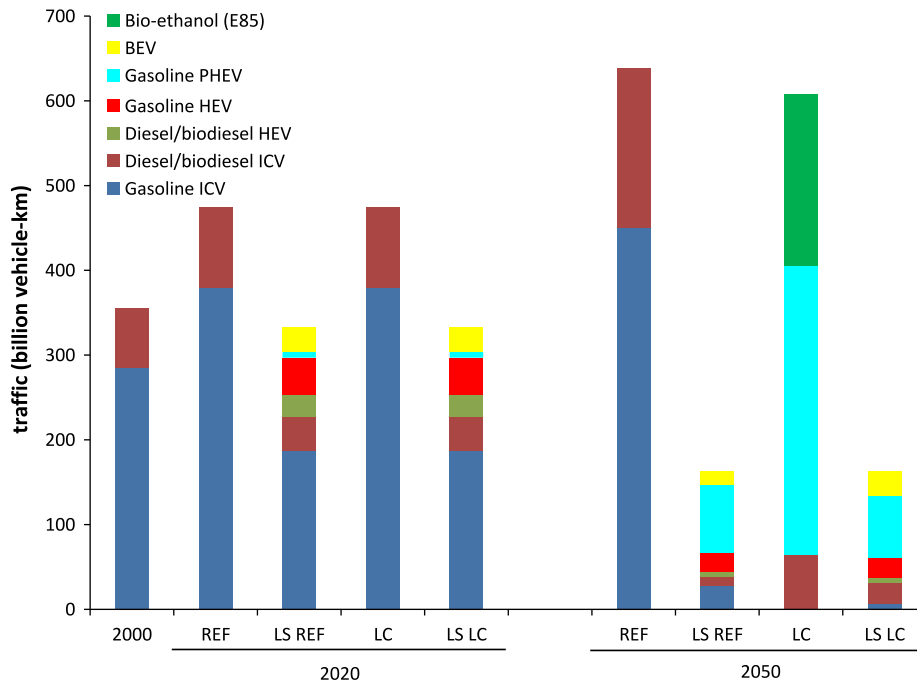


Fig. 4. Car vehicle type by distance driven in different scenarios and years, MED results. REF—reference, LS REF—Lifestyle reference, LC—low carbon constrained, LS LC—Lifestyle low carbon constrained, BEV—battery electric vehicle, HEV—hybrid electric vehicle, PHEV—plug-in hybrid electric vehicle and ICV—internal combustion vehicle.

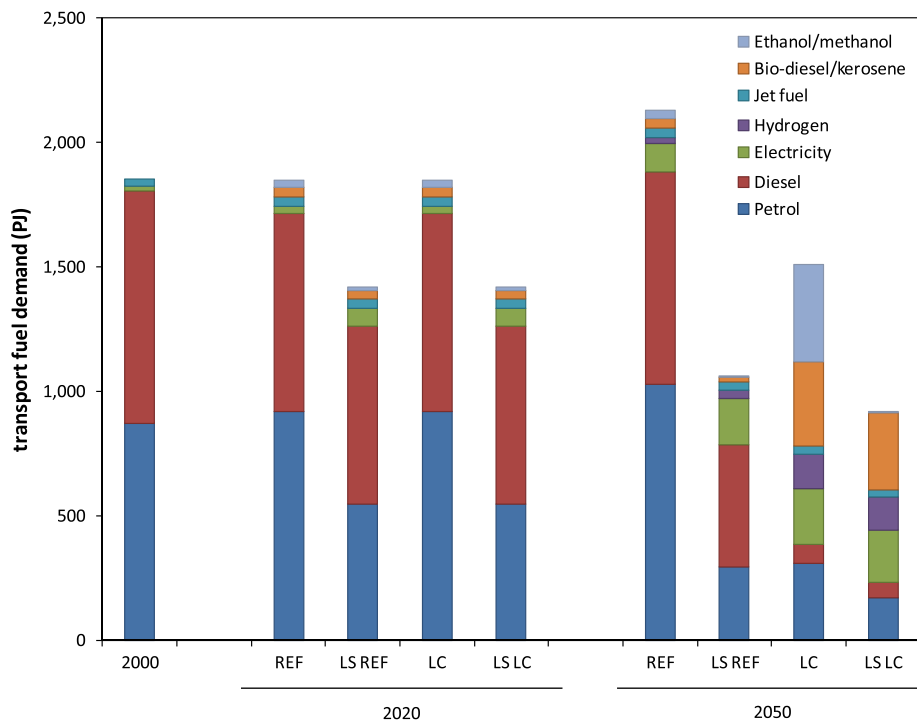


Fig. 5. Transport fuel demand (PJ) by transport fuel in each scenario in 2020 and 2050, MED results. REF—reference, LS REF—Lifestyle reference, LC—low carbon constrained and LS LC—Lifestyle low carbon constrained.

Bio-fuels only play a major role in the carbon constrained cases (LC & LS LC). This is a result of the availability of unconstrained blending of second generation biodiesel and the assumption within MED that bio-fuels have zero net carbon emissions (much liked by a scenario modelling an 80% cap on emissions), while in the reference cases (REF and LS REF) demands decrease in line with petrol and diesel demands. A high-level blend of bio-ethanol and petrol (E85) used in flex-fuel cars only appears from about

2035 in the core constrained case (LC), accounting for 26% of total transport fuel demand in 2050—12 times more than in the reference case (REF). In the related Lifestyle variant (LS LC), lower demand and greater preference for efficient vehicles means that biodiesel hybrids are preferred (see also Fig. 4).

Hydrogen also only plays a major role in the constrained cases (LC & LS LC) in the long term (2050), which sees three quarter of the truck fleet switching from diesel/biodiesel ICE to hydrogen

fuel cell powertrains. There is a minor role for hydrogen fuel cell trains from 2030 in the *unconstrained* cases, where hydrogen powers a third of rail energy demand by 2050.

6. Implications for carbon emissions and the wider energy system

Overall, the unconstrained Lifestyle variant (LS REF) resulted in a 26% and 58% reduction in transport CO₂ emissions *at source* (or direct, tailpipe) by 2020 and 2050 compared to the core reference scenario (REF) levels (Fig. 6). Importantly, the reduction in these emissions happens *early on* and mostly *before* 2030, after which transport CO₂ emissions stabilise. CO₂ emissions at source notably exclude upstream emissions from power generation, which for the whole economy are also 7% and 17% lower by 2020 and 2050 than baseline (REF) levels. This suggests that the higher uptake, use and associated electricity demand of ‘plugged-in’ vehicles is more than offset by the decreasing demand for (car) travel overall.

As for the carbon constrained scenarios, the results shown in Fig. 6 suggest that in the core constrained reference case (LC) the transport sector only starts to pull its weight from around 2030, mainly as a result of the widespread use of second generation bio-fuels. The gradually tightening decarbonisation targets prior to 2030 are met by other sectors. In contrast, the constrained Lifestyle case (LS LC) follows the same carbon emissions trajectory as the unconstrained Lifestyle case (LS REF) up to about 2040, after which transport CO₂ fall sharply to levels that are even 37% lower than in the core carbon constrained (LC) scenario.

Across the whole economy in 2050, carbon emissions are 30% lower in the unconstrained Lifestyle case (LS REF) compared to REF. As can also be seen by the late divergence of the LS REF and the LS LC lines in Fig. 6, this in turn makes the achievement of radical carbon reductions such as the 80% easier, with fewer changes required to the transport or energy systems. Indeed, total energy demand between the two Lifestyle variants is comparable (between 3800 and 4400 PJ), it is mainly the virtual elimination of diesel in favour of biodiesel that takes place in order to meet the carbon constraint, although the use of bio-fuels is still only half that taken up in the core constrained (LC) scenario. In addition, the Lifestyle constrained case (LS LC) requires around 25% less electricity than the LC scenario, thus requiring a lower rate of

growth in the construction of large scale centralised zero carbon electricity technologies such as carbon capture and storage, nuclear and wind capacity.

This has important implications for climate mitigation policy. A scenario that involves voluntary lifestyle change will place much less pressure on policy to require rapid (and potentially disruptive) technical change, including technologies at the point of energy use. The assumption that encouraging lifestyle change presents more problematic issues for policy makers than a ‘top down’ technical solution is therefore challenged by these findings.

The most significant impact of lifestyle change on the wider energy system, compared to the core scenarios, is due to reductions in the overall demand for final energy, particularly for oil derived fuels in transport. When changes in both the residential and the transport sectors are added, total final energy demand is 15% lower than the REF scenario by 2020 and 30% by 2050, with beneficial effects for energy system costs, carbon emissions and energy import requirements. Lifestyle change alone (without a carbon constraint) has an effect on total final energy demand akin to an 80% carbon constraint with no lifestyle change. The effects are most strong for the fuels where import dependence is most likely. In the unconstrained Lifestyle case (LS REF), by 2050, gas use is 34% lower and oil use 54% lower than in REF. The implications for energy security are therefore very substantial. This compares interestingly to findings reported elsewhere that explicit concerns about energy security would lead to greater attention to reducing demand (Skea and Ekins, 2009), i.e. the same correlation but with opposite causality. The implications of concerns about a combination of climate change and energy security merit further research.

7. Summary of results

Modelling of radical changes in lifestyle led to a 74% reduction in distance travelled by car by 2050. The use of all other surface transport modes increases, apart from a 12% fall in distance travelled by trucks. The reduction in car travel comes about as a result of significant mode shifts, particularly to bus travel towards the latter half of the period (184% increase in vehicle kilometres) and cycling and walking. The take-up of cycling as a mode of transport reaches the same level in terms of mode split by 2050 as

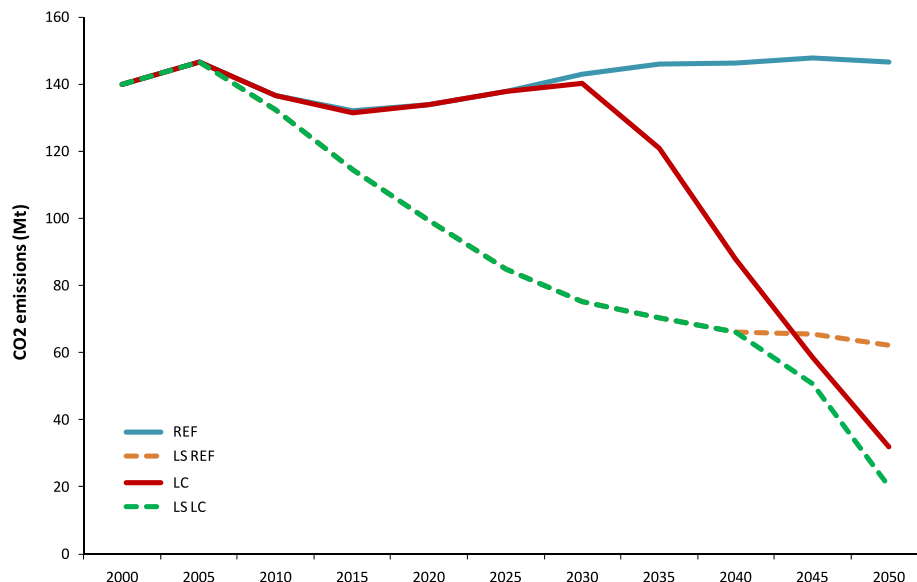


Fig. 6. Projections of CO₂ emissions (Mt) at source from domestic transport in each scenario, MED results. Note: These are source (or direct, or tailpipe) emissions and thus exclude emissions from power generation.

Table 3
Summary results of the Lifestyle variant (LS REF).

	2007	2020	2050
Average distance travelled (km per person p.a.)	11,484	10,756	9035
Avg. car occupancy	1.58	1.75	1.94
Mode split (% distance)			
Cars and motorcycles	83%	71%	40%
Slow modes	3%	9%	28%
Bus and rail	14%	20%	32%
Share of new 'large cars'	15%	0%	0%
On-road fuel efficiency:	<i>km affected</i>	<i>km affected</i>	<i>km affected</i>
Cars, 8% better per km	4%	46%	62%
Vans, 8% better per km	4%	50%	70%
Trucks, 4% better per km	4%	50%	70%
Air demand growth (p.a.)	2.5%	1.0%	0.0%
Technology choice, e.g. share of <i>new</i> cars by propulsion	99% ICE	16% EV 28% HEV 8% PHEV	9% EV 18% HEV 46% PHEV
Transport CO ₂ at source, reduction over baseline (REF)	n/a	–26%	–58%

is the norm in the Netherlands today (40% of all trips). However, mode shift is combined with destination shifting as trips are either totally abstracted from the system through virtual travel or shorter as a result of localisation.

UK road vehicles are getting 'plugged-in' as PHEV cars reach nearly 50% market share of total car fleet by 2050 and 26% of road transport energy demand is met by PHEV by 2050. An unconstrained Lifestyle case (LS REF) implies that 10% of the UK car park will be able to connect to the grid by 2020 and 36% by 2030. There is no change compared to the REF scenario in the short term, as the numbers remain constrained by the lack of vehicle and infrastructure availability. For road freight, all of the scenarios imply that nearly half of the UK van and HGV fleets will be able to connect to the grid by 2030. To achieve the level of production and sales demanded by the scenarios, market conditions and necessary infrastructure to support the rollout of grid-connected vehicles, particularly PHEV, beyond urban areas will need to be in place. The period after 2020 will need to see an increase in the range of vehicles available to consumers and freight operators in order to sustain the growth momentum. In addition, car owners downsize and drivers respond to the on-road fuel efficiency programme and speed limit enforcement as the car fleet alone uses 5–6% (2020) and 11–12% (2050) less energy per km driven.

Overall, the LS REF scenario results in a 26% and 58% reduction in transport CO₂ emissions by 2020 and 2050 from the levels in the unconstrained core reference scenario (REF). The key outputs are summarised in Table 3.

8. Discussion and conclusions

This paper has investigated the role of pro-environmental lifestyle change for the UK energy system to 2050 by concentrating on changes in transport activity. It starts with the premise that society and human behaviour change over time, sometimes in unpredictable directions, and therefore there is a wide variety of possible future levels of energy service demand and end use technology choice. We also assume that energy using behaviours are the result of the interaction between personal decisions and the social and economic context including the available technologies, physical infrastructures and public policy. Our analysis is therefore socio-technical.

Our analysis contrasts the techno-economic driven approach to carbon emissions reduction with the results of a novel and integrated modelling approach which characterised patterns of travel behaviour consistent with a more sustainable, low energy

service demand society. This necessarily involves 'what if' scenario planning, which is not intended to allow the emergence of a single vision for the future but rather to challenge policy makers to consider how to formulate policies that can be robust in the face of such future uncertainty and thus positively contribute to society's evolution. In particular, this analysis implies that the role of policy is not restricted to influencing pricing and technological change but also has a role in shaping lifestyles and energy-using behaviours.

We have used an innovative methodology to combined the strength of detailed bottom-up modelling and a sectoral modelling approach with an optimisation model of the whole UK energy system. By using a structured 'storyline' approach and breaking down current travel choices into their constituent journey purposes, lengths and modes, we reflected the potential impact that long term structural changes in society and concurrent changes in individual priorities and preferences might have on the volume and composition of travel activity. This incorporated non-price determinants of behaviour (values, norms, fashion; trust; knowledge) and non-consumptive factors (time use; mobility; social networking; policy acceptance). We have assumed changes to behaviour that we judge reasonable in an advanced economy, based on observation of energy-using activities across the developed world today. And we have assumed rates of change that seem feasible taking into account the need for both technologies and energy-using practices to diffuse and the external constraints to this, e.g. the need to change existing infrastructure.

Our results revealed a different future in which final energy demand in the transport sector would be halved by 2050 compared to the reference case. This implies rates of change (energy demand decreases) of just below 2% annually. Moreover, despite the more rapid uptake of plug-in and battery electric vehicles and the larger share of electricity in final energy demand, the Lifestyle variants of our core scenarios showed a future in which the need for massive electrification to meet carbon targets would be significantly reduced. Thus, under a scenario where energy demand is reduced, electricity sector decarbonisation could be delayed. Impacts on carbon emissions from transport sector at source are similar to those on final energy, i.e. a 58% reduction without a carbon constraint, and with more early progress. We conclude that lifestyle change can make a significant contribution to delivering UK carbon emission goals, and assist early action, but that alone it is insufficient to deliver an 80% reduction goal, as this requires a wider transformation of the energy system.

The emphasis on patterns of activity and changes to individual preferences and societal norms outlines the key trade-off to be made between the more aggressive pursuit of energy efficiency and demand reduction (Skea and Ekins, 2009). Given the many uncertainties and risks involved in decarbonising our energy supply, there are strong arguments for pursuing both demand and supply side solutions in order to make the path to an 80% reduction more sustainable and potentially more certain.

Yet current market and regulatory arrangements sit uneasily with the requirement to tackle behaviour change let alone the transformational change required. Even though the role of behaviour change in carbon emissions reduction is already established in policy analysis, the dominance of techno-economic analysis leads to a favouring of carbon pricing and technical solutions. Analyses based in these disciplines therefore sometimes give the impression (and in some cases even assumes explicitly) that 'policy cannot change behaviour'. However, there is no substance, theoretically or empirically, for such an assumption.

The policy agenda for lifestyle change is less well developed than the equivalents for pricing and technological change. But the broad principles of what works are increasingly well-understood. For instance, studies of individual travel behaviour demonstrate that behaviour is constantly changing in both sustainable and unsustainable directions (Goodwin, 1999). These changes are not equal and result in a net change in aggregate travel behaviour which, so far, has led to unsustainable patterns. It is important therefore to recognise the existence of churns in travel behaviour and to attempt to develop appropriate policies to target different groups of travellers with the relevant transport policies in order to improve the transport system. Other evidence points to the potential malleability of travel behaviour. For instance, Cairns et al. (1998) examined over 70 case studies in 11 different studies where road space had been reallocated due to sudden shocks (e.g. earthquakes) or planned (e.g. pedestrianisation schemes) and found across all case studies, the average traffic reduction in the total local network soon after the change was 22%, with a median of 11%. Similarly, we know that the traffic reduction after the London congestion charge was in the order of 15% immediately after its introduction (TfL, 2007), car traffic reduced by 39% on motorways overnight after the 'fuel protests' in the UK in 2000 (Hathaway, 2004), and cycling increased dramatically after the terrorist attacks in London in 2005 (although the trend was already upward).

However, despite mounting evidence of the key role that behaviour change can play in decarbonising the transport sector (see Anable, 2005; Hickman and Banister, 2007; Cairns et al., 2008; Koehler, 2009), UK policy gives far less attention to demand-side measures to reduce total kilometres travelled or, shift to less carbon intensive modes of transport. But, if we cannot define sustainable lifestyles and incorporate non-price driven behavioural motivations into our analytical frameworks, it will continue to be hard to assess the effectiveness of policy measures taken to move towards them and the reluctance to adopt them will continue. This paper goes some way to fulfilling this role. It is however, acknowledged, that a scenario that relies on such fundamental shifts in activity patterns, preferences and price signals will have far reaching implications on many other aspects of society and economy such as wider consumption practices (e.g. leisure, food consumption and work practices), preferences for business and residential location and knock-on land values. Therefore, in addition to understanding the behavioural and public policy processes to bring about lifestyle shifts, there is much more that needs to be done to understand the system-wide energy implications of fundamental socio-technical transitions in transport as well as other sectors.

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