Lifestyle, efficiency & limits: modelling transport energy and emissions using a socio-technical approach

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Abstract
The Paris climate change agreement and 'dieselgate' emissions scandal in the US have prompted policy makers, regulators and industry to re-evaluate strategies to meet climate change mitigation and air quality goals. While a wide range of supply and demand policies have been proposed at both national and subnational/local levels, implementation and even the supporting research evidence have been lagging ambition in many parts of the world. It is well known that societal transport energy consumption and related emissions are influenced by technical efficiency, the carbon/pollutant content of energy and by 'lifestyles' and socio-cultural factors. However, only a few attempts have been made to operationalise these insights into models of future transport energy demand or even scenario analysis. In particular, insights into human behaviour, lifestyle change and the important role of individual attitudes and perceptions are often overlooked by policy makers. This paper addresses this gap in research and practice by presenting a quantitative scenario exercise using an integrated transport-energy-environment systems model to explore four contrasting futures for Scotland that compare 'lifestyle' change and socio-cultural factors against a low carbon technology focussed transition pathway using a socio-technical approach. We found that radical demand and supply strategies can have important synergies (and potential trade-offs) between reducing life cycle greenhouse gas and air quality emissions. Lifestyle change alone (without an EV transition) has a similar effect on transport carbon and air quality emissions than a transition to EVs with no lifestyle change. Yet both have limits to meeting future targets, which may only be achieved with a combined strategy of radical change in travel patterns, mode choice, vehicle occupancy and on-road driving behaviour with high electrification and phasing out of conventional petrol and diesel road vehicles.

Introduction
The somewhat unexpected outcomes of the 2015 Paris climate change agreement and the US 'dieselgate' emissions scandal have prompted policy makers, regulators and industry to re-evaluate strategies to meet climate change mitigation and air quality goals. A wide range of supply and demand policies have been proposed at both national (e.g. graded purchase taxes favouring electric vehicles, scrappage rebates for replacing diesel vehicles with electric vehicles) and subnational/local levels (e.g. phasing out or banning of diesel/petrol vehicles, air quality driven speed limits). However, policy implementation has been lagging ambition, and consumer response has been lacklustre, in many parts of the world. At the same time, there is consensus that societal transport energy consumption and related emissions are not only influenced by technical efficiency and the carbon/pollutant content of energy that many of the above policies target, but also by 'lifestyles', socio-cultural factors (e.g. expenditure patterns, localism, multiple car ownership, (un) acceptability of air travel, social norms, habits and the ageing population) and, crucially, by changes in the number of and composition of the population. As only few attempts have been made to operationalise these insights into models of future transport energy demand (Weber and Perrels 2000, Anable,

Brand et al. 2012, Chitnis and Hunt 2012, Skippon, Kinnear et al. 2016), there is a methodological gap between the perceived importance of these factors for transport energy demand and quantitative modelling frameworks or even scenario analysis.

Electrification of the passenger vehicle and light goods vehicle fleets is a key strategy and viewed as necessary to achieve decarbonisation and cleaning up of the transport sector. The UK and Scottish policy focus on vehicle technology reflects other global transport modelling exercises that depend upon between 40 % to 90 % market penetrations of technologies such as plug-in hybrid electric (PHEV) and full battery electric vehicles (BEV) between 2030 and 2050 (Scottish Government 2013, IEA 2015, CCC 2016). Although scenario exercises such as these are used to explore the potential CO_2 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.

Scotland is an interesting case study as it has highly ambitious and legislated climate change and air quality targets, and a sub-national governance structure (Anderton 2012) that allows subnational and local policies to be implemented that may go beyond UK and EU plans and policies (Melo 2016). Indeed existing plans by the Scottish Government include 'softer' demand policies (such as 'smarter choices') and promotion of structural changes of the transport system that are often ignored (Scottish Government 2013, Scottish Government 2013, Scottish Government 2017).

This paper addresses this gap in research and practice by presenting a quantitative scenario exercise using an integrated transport-energy-environment systems model to explore four contrasting futures that 'pitch' lifestyle (demand) change against a low carbon technology-focussed transition pathway using a socio-technical approach. By doing so it demonstrates the likely synergies (and potential trade-offs) between reducing life cycle greenhouse gas and air quality emissions using different demand and supply strategies. Specifically, it models future lifestyle and structural changes in the transport system, travel demand changes due to socio-cultural changes, the phasing out of highly polluting vehicles and low carbon pricing incentives. Techno-economic driven scenarios are contrasted with one in which social change is strongly influenced by concerns about energy use, the environment and wellbeing so that transport energy service demand is at a significantly lower level by 2050 than in the 'business as usual' assumptions of other pathways. The paper thus challenges policy makers to consider the very dominant focus on technical solutions.

Approach, methods and data

APPROACH AND CHOICE OF MODELLING TOOL

To achieve the above objectives we developed a Scottish version of the UK Transport Carbon Model (UKTCM), a previously developed transport-energy-environment system modelling framework that has been applied in a number of policy modelling studies (Anable, Brand et al. 2011, Anable, Brand et al. 2012, Brand, Tran et al. 2012, Brand, Anable et al. 2013). This new Scottish Transport Energy and Air pollution Model (STEAM) integrates a detailed transport demand model, household car ownership model, vehicle consumer choice model, vehicle stock evolution model and vehicle and fuel life cycle emissions model in a single scenario modelling framework. STEAM has the ability to place the potential phasing out of petrol and diesel vehicles and electrification of the car market in the context of radical changes in travel behaviours on the basis of their transport, energy and lifecycle emissions impacts. It may therefore have a much broader remit and wider range of applications in scenario and policy analyses than, for instance, the top-down 'ASIF' (Schipper 2011) decomposition framework, sectoral models that lack endogenising consumer behaviour (Rogan, Dennehy et al. 2011, Fontes and Pereira 2014), or integrated assessment models that by and large favour technology solutions and fuel shifts over travel activity and consumer behaviour modelling (Oxley, Dore et al. 2013, Creutzig 2015). The modelling framework is briefly summarized below, with further details published in (Brand, Tran et al. 2012, Brand, Cluzel et al. in press).

STEAM is a highly disaggregated, bottom-up modelling framework of the transport-energy-environment system. Built around a flexible and modular database structure, it models annual projections of transport demand and supply, 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 2100 (NB: our time horizon for this study was 2012 to 2050). It takes a holistic view of the transport system, built around a set of exogenous scenarios of socio-economic, socio-technical and political developments. The model is technology rich and provides projections of how different demand segments (distance travelled by purpose, mode and trip length) change over time as well as how different vehicle technologies evolve over time for 770 vehicle technology categories, including 283 car technologies such as increasingly efficient gasoline internal combustion engine vehicles (ICEV), battery electric vehicles (BEV), and plug-in hybrid electric vehicles (PHEV). The UK version of STEAM, the UKTCM, played a key role in developing the *Energy2050* 'lifestyle' scenarios (Anable, Brand et al. 2011, Anable, Brand et al. 2012) for the UK Energy Research Centre (UKERC) and in exploring the effectiveness of low carbon car purchasing incentives in the UK (Brand, Anable et al. 2013). An overview of the model has been published in Brand et al. (2012).

SCENARIO DEVELOPMENT: THE CASE OF SCOTLAND

STEAM was applied in a Scottish case study to explore and compare the travel, energy use and emissions impacts of alternative scenarios of radical behaviour change vs. an ambitious electrification pathways for the Scottish road vehicle fleet using a socio-technical approach to scenario development. We first developed storylines and then quantified four core scenarios, as shown in Table 1.

Reference pathway (REF) – key data and assumptions

STEAM was calibrated to Scottish national statistics for the year 2012 (DfT 2014, ONS 2015). We obtained the 'protected' (i.e. more detailed) National Travel Survey dataset and used SPSS

Table 1. The four socio-technical scenarios for Scotland.

Reference (REF)	**Lifestyle change (LS)**
Projection of transport demand, supply, energy use and emissions as if there were no changes to transport and energy policy beyond October 2016	Radical change in travel patterns and mode choice leading to relatively fast transformations and new demand trajectories
Electric vehicle promotion and petrol/diesel 'phase-out' (EV)	**Combined lifestyle and EV pathway (LS EV)**
Pathway of 'high electrification' + phasing out of conventional oil based ICEVs: range of measures incl. pricing, taxation, investment, EV infrastructure, scrappage/ purchase tax on future diesel and petrol cars, changing consumer preferences	Integration of radical change in travel patterns, mode choice, high electrification and phasing out of conventional petrol and diesel road vehicles

v21 to derive trip rates, distance travelled and mode splits for Scotland in 2012. The 'Reference' scenario (REF) broadly depicts a projection of transport demand, supply, energy use and emissions as if there were no changes to transport and energy policy beyond October 2016. It was modelled using STEAM based on exogenous assumptions and projections of socio-demographic (incl. demand effects of an ageing of the population), economic, technological and (firm and committed) policy developments, including the recently simplified vehicle road tax and relatively complex CO2-graded company car tax regimes. Economic growth data up to 2015 were based on government figures. Future GDP/capita growth were assumed to average 1.35 % p.a. up to 2050. Transport demand projections were modelled based on no changes in trip patterns (i.e. trips and distance travelled per person p.a., and mode split) apart from lower commuting levels due to an ageing population, and average demand elasticities (of GDP/capita, population and generalized cost) for international air and freight transport. Fuel price and retail electricity price projections were based on 2014 UK Government forecasts (DECC 2014). Annual road tax and road fuel duties were assumed to remain constant at 2016 levels. Following an approach commonly used in technology futures and modelling studies (European Commission 2005, WEC 2007, Strachan and Kannan 2008, Strachan, Kannan et al. 2008, Fulton, Cazzola et al. 2009, UK Energy Research Centre 2009), pre-tax vehicle purchase costs were kept constant over time for established technologies and gradually decreased for advanced and future technologies, thus exogenously simulating improvements in production costs, economies of scale and market push by manufacturers.[1] For example, average purchase prices for BEV cars were assumed to decrease by 2.8 % pa from 2015 to 2020, by 1.6 % pa until 2030 and 0.6 % pa until 2050. The Reference scenario further assumed gradual improvements in specific fuel consumption and tailpipe CO2 emissions per distance travelled. The rates of improvement were based on technological innovation driven entirely by market competition, not on policy or regulatory push.[2] Fuel consumption and CO2 improvement rates for future car vintages were assumed to be 1.5 % p.a. – a somewhat lower and more conservative rate than the average rate of 4 % p.a. based on test-cycle data for all new cars between 2008 and 2013 (NB: 'real world' improvements have been significantly lower). Indirect emissions from fuel supply and vehicle manufacture, maintenance and scrappage have been updated with data from a recent UK-based review (Kay, Hill et al. 2013). Finally, the default electricity generation mix follows central government projections (mainly natural gas, wind & nuclear – with some CCS coal and gas by 2030), implying the carbon content of retail electricity is gradually decreasing from about 390 g CO2/kWh in 2015 to about 160 g CO2/kWh in 2030. In absence of any government projections beyond 2030 we have assumed that the carbon content stays constant at that relatively low level out to 2050.

1. The assumption that alternative technologies improve (cost, energy and environmental performance, consumer preferences) at a faster rate over time applies equally to all scenarios modelled here, not just the reference scenario.

2. This implies that the EU mandatory agreement on new car CO2 emissions would not be met. However, separating innovation by competition and innovation by regulation/policy push is slightly arbitrary here as the effects are never easy to untangle.

The 'lifestyle' (LS) scenario: storyline and travel demand 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 (Schafer 1998). However, based on evidence relating to actual travel choices, the lifestyle variant explored a world in which social change 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 (Kurani, Turrentine et al. 1994, Anable 2005) was deemed to be a dominant driver of energy service demand from transport.

The 'lifestyle' consumer is more aware of the whole cost of travel and the energy and emissions implications of travel choices and is sensitive to the rapid normative shifts which alter the bounds of socially acceptable behaviour. Consequently, the 'Lifestyle' scenario assumed the focus would shift away from mobility towards accessibility, and that the quality of the journey experience rather than the quantity and speed of travel would become more important. Triggered in part by deteriorating conditions (e.g. sensitivity to congestion and air quality concerns) and catastrophic events (increased frequency of flooding), social norms elevate cleaner and more efficient (in transport terms) modes such as active travel and public transport 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 car-based systems running on petrol and diesel. 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 express 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 accessibility as a service (AaaS) are embraced. This includes Uber, car clubs[3] and the tendency to hire shared PHEV 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. There is increasing acceptance of restrictive policies in the context of more choice for local travel as the alternatives are improved. Some services return to rural areas, but it becomes more common to carry out personal business and shopping online. Small-scale technology facilitates relatively rapid behavioural change. Information and Communication Technology (ICT: telematics, in-car instrumentation, video conferencing, smartcards, 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, Heptonstall 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, which somewhat offsets the positive effects of decongestion from fewer cars on the road. There is some shift towards rail freight and passenger rail from domestic air.

Combined with the shifts towards active modes and different models of car ownership, this amounts to significant lifestyle shift. The consequences for travel patterns of these shifts were first analysed using the STEAM travel demand model, which took as its starting point the figures for current individual travel patterns based on Scottish data in the UK National Travel Survey (ONS 2015). 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 Scotland.

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 Scotland within the timeframe to 2050. Careful consideration and a more conservative approach was used to take account of specific climate, cultural and topographic factors with regards to Scotland. This implies neither incremental nor step changes in behaviour. Indeed, 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 (Crompton 2008, CCC 2016, Maione, Fowler et al. 2016). Instead, this Lifestyle scenario outlines *radical* change leading to relatively fast transformations and new demand trajectories.

The high electrification pathway (EV)

This scenario combines a transformative pathway developed for the UK's Committee on Climate Change (CCC) and focusing on supply measures for plug-in vehicles as an alternative to oil-based vehicles with a scrappage/purchase tax aimed at phasing out petrol/diesel vehicles (ICEV, HEV but not PHEV) out of urban areas by 2030. The analysis by the CCC (CCC 2013, CCC 2015) suggested plug-in vehicle deployment targets for 2020 and 2030 at 9 % and 60 % respectively. A small number of scenarios were run using STEAM in an iterative process that led to the high electrification scenario underlying EV. This implied transformational change including: ultra-low emission vehicles (ULEVs) being available in all vehicle segments and by all major brands by 2030; nationwide consumer awareness and acceptance of ULEVs by the 2030s driven by comprehensive awareness campaigns and the 'neighbourhood effect'; significant investment and repositioning towards ULEVs by the main vehicle manufactures; significant investment in recharging infrastructure (home charging, fast charging stations in and beyond Scotland); reduced (perceived) recharging times; and continued and improved 'equivalent value support' (taxation, fuel duty) for ULEVs for both private and company/fleet buyers. Petrol/diesel vehicles are gradually phased out through higher purchase/scrappage taxes, reinforced by low emission zones and increased parking charges in cities/towns. Generally, however, the policy environment is one of 'push and pull' as fiscal and regulatory sticks are combined with the carrot of infrastructure investment (ULEV vehicle choice and availability, home charging, fast recharging stations).

The integrated scenario (LS EV)

This combines radical change in travel patterns, mode choice, vehicle occupancy and on-road driving behaviour (as in LS) with high electrification and phasing out of conventional petrol and diesel road vehicles (as in EV). Essentially, lower demand is met by lower carbon/energy supply.

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

Impact on travel patterns and vehicle technology

The impact on travel patterns and vehicle technology choice can be divided into five key areas of energy service demands from transport: (1) changing passenger travel patterns, (2) air travel, (3) freight transport, (4) driving style and on-road fuel efficiency, and (5) vehicle technology choice.

CHANGING SURFACE PASSENGER TRAVEL PATTERNS

The lifestyle scenarios (LS, LS EV) resulted in a 52 % 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 6 % fall in distance travelled by taxis. The reduction in car travel comes about as a result of significant mode shifts, particularly to bus travel towards the latter part of the period (+85 % for local bus, +260 % for express coach) and cycling and walking. 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.

Figure 1 shows how people become progressively more 'multi-modal' by the end of the period in the LS scenarios. In 2030, the car is still used for the majority of distance travelled as a driver or passenger (61 %), but this drops to 40 % by 2050. At the same time, cycling goes from accounting for less than 1 % to more than 8 % of distance travelled, mainly replacing short car trips under 5 miles. This surpasses levels seen today in countries regarded as demonstrating best practice in this area: in 2006 an average Dutch person cycled 850 km per 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 these lifestyle scenarios assume. If cycling and walking are added together, 'slow modes' account for 17 % 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.

AIR TRAVEL

Growth in domestic flights are assumed to slow and eventually saturate due to growing unacceptability of flying short distances leading to increasing use of high speed rail (assuming HS2 will be operational by the 2030s) and express coaches. Flying becomes a luxury and increasingly uncompetitive on the basis of time and cost for most domestic routes as the price increases and rail and coach (taking on road capacity left by less car travel) travel are improved. Domestic air-miles in the lifestyle (LS, LS EV) variants are thus 4 % and 21 % lower in 2030 and 2050 respectively than in the REF and EV cases. Frequent international air travel is also increasingly becoming unacceptable so that air-miles in the lifestyle variants are 4 % and 15 % lower in 2030 and 2050 respectively.

FREIGHT TRANSPORT

Van ownership and use continues to increase as it did in the decade prior to 2012, growing by 54 % by 2050 over the 2012 levels. The move towards a service economy and more teleshopping fuel this trend. However, as van technology and urban delivery logistics improve, their use is maximised and van-km decrease somewhat. Town/city centres increasingly ban heavy goods vehicles but allow electric vans, and local traffic regulations will give priority to professional home delivery and consolidated urban distribution with clean vehicles. As a result, the overall distance travelled by vans will decrease by 24 % by 2050 in the LS and LS EV scenarios when compared to the REF and EV scenarios. Heavy goods vehicles are still set to grow (by 8 % between 2012 and 2050) due to economic and population growth, but mainly as a result of increased load factors through business-led vehicle utilization measures and consolidation centres (Hickman and Banister 2007), overall distance travelled by these vehicles will fall by 11 % (2030) and 24 % (2050) when compared to baseline. Rail and waterborne freight play a bigger role, mainly due to mode shift from roads.

DRIVING STYLE AND ON-ROAD FUEL EFFICIENCY

In the Lifestyle scenarios, 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

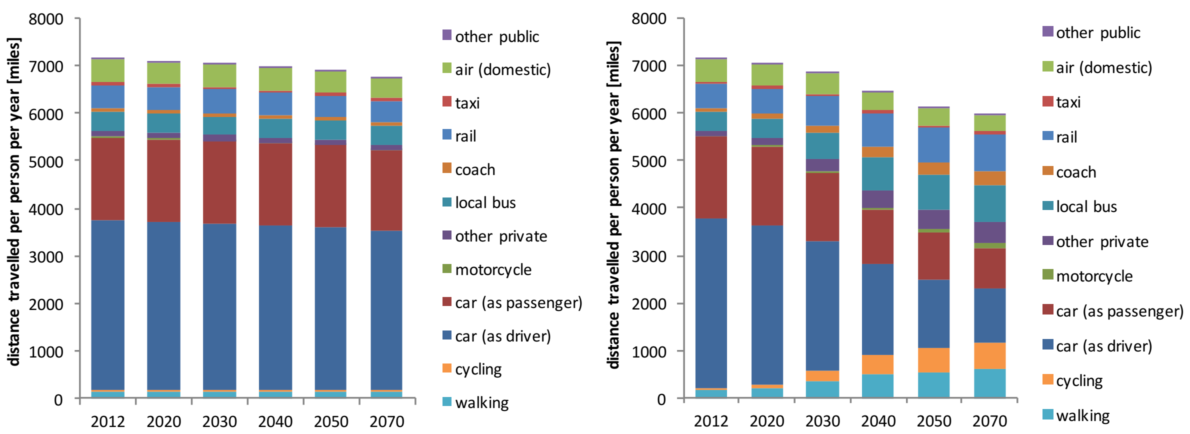

Figure 1. Average distance travelled per person per year by transport mode, REF and EV scenarios on the left, LS and LS EV scenarios on the right.

limiters, fuel economy meters and tyre pressure indicators. We assumed that new drivers will start to practice eco-driving 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 cars, this increases from 3,6 % in 2012 to 41 % in 2025, then levelling off at 62 % from 2035. For those miles affected, an 8 % efficiency improvement is assumed, which is at the lower end of the evidence base (Gross, Heptonstall 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.

VEHICLE TECHNOLOGY CHOICE AND USE

In the EV and LS EV scenarios, private, fleet and commercial buyers increasingly prefer electric vehicles over conventional internal combustion vehicles, fuelled by a co-evolving EV market with increasing availability and performance of lower carbon vehicles, investment in home and fast stations recharging infrastructure, and supporting low carbon pricing policy for ULEVs. Petrol and diesel ICEVs (and HEVs) are increasingly 'priced out' of the market as cities start banning conventional vehicles from urban areas. This implied transformational change that was modelled as: ULEVs being available in all vehicle segments and by all major brands by 2030; nationwide consumer awareness and acceptance of ULEVs by the 2030s; significant investment and repositioning towards ULEVs by the main vehicle manufacturers; significant investment in recharging infrastructure; reduced (perceived) recharging times; gradually increasing purchase taxes for conventional (ICEV, HEV) cars, vans and urban buses; and continued and improved equivalent value support (i.e. lower company car tax, road tax and purchase tax) for ULEVs for private and company/fleet car and van buyers. The detailed assumptions are similar to those reported in previous work on exploring pathways to meeting national climate change mitigation targets (Brand 2016, Brand, Cluzel et al. in press).

As a result, in both 'EV' and 'LS EV' ICEV and HEV continue to be the main focus in the short term before ULEV (essentially PHEV and BEV) reach approx. 10 % of market share in the early 2020s, driven by the fleet and early adopter markets. Take-up by the mass market and so-called 'user-choosers' (Brand, Cluzel et al. in press) in the late 2020s mean that PHEV car sales reach the 50 % mark by 2032 before increasingly better performing BEV take over as the dominant choice of vehicle from about 2040, especially for cars and vans in urban areas. This purchasing behaviour is illustrated for cars in Figure 2, showing current and projected new car sales by propulsion type for the four scenarios. While in 2016 only about 2 % of new cars were plug-in vehicles, the 'EV' and 'LS EV' scenarios suggest that by 2030 63 % of new cars could be plug-in vehicles. By 2050, 85 % of new cars could be plug-in, a direct effect of favourable market and policy conditions for plug-in vehicles and the phasing out of conventional ICEV and HEV in urban areas. Note that the 'lifestyle' scenarios result in much lower overall car ownership (and therefore sales) levels, reflecting 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.

The changes in overall traffic levels, modal shares and the increased demand for lower carbon vehicles are further illustrated in Figure 3, showing Scottish road vehicle traffic (in billion vehicle-km) in the 'REF' (on the left) and 'LS EV' (on the right) scenarios. In 'LS EV', total road vehicle-km decreased considerably (while they increased by 25 % in 'REF'), and conventional ICEV and HEV technology is gradually replaced by PHEV and, later, BEV traffic. While by 2025 8 % of car traffic was PHEV or BEV, this share increased rapidly to 29 % (2030) and further to a dominating 84 % by 2050. As for vans, advanced ICEV, PHEV and, slightly later, BEV technologies dominate urban delivery traffic over the assessment period. HEV technology only ever reach 5 %.

Impact on transport energy use

The higher uptake of lower and zero carbon vehicles combined with efficiency gains, mode shifts and significant alterations to work, shopping and leisure travel patterns as modelled in the combined 'LS EV' scenario result in final energy demand being nearly halved from this sector by 2050 compared to the reference case (REF) (Figure 4). Lifestyle change on its own reduced transport energy demand by 14 % by 2030 and by 31 % by 2050 compared to the reference case (REF). Reductions were somewhat lower for the EV technology scenario (EV) at 8 % (2030) and 25 % (2050) as travel demand increased (EV) rather than decreased (LS). When compared to baseline (REF) the demand for conventional fuels (petrol, diesel) was 35 % lower in 2050 in the lifestyle scenario (LS) and less than half in the combined lifestyle and EV technology case (LS EV). By comparison, electricity demand grew steeply in the EV scenarios, rising from its 2012 base of just 1,3 % (largely rail) to around 20 % of total fuel demand by 2050 in the EV and LS EV scenarios (Figure 4).

Impact on transport carbon emissions

The lifestyle (LS) scenario resulted in a 12 % and 28 % reduction in transport CO_2 emissions at source (i.e. direct) by 2030 and 2050 compared to baseline (REF) levels (Figure 5), with absolute reductions over 2012 of 25 % (2030) and 46 % (2050). This was largely due to reductions from car emissions, but somewhat offset by increases in bus, rail and motorcycle emissions due to mode shift. The technology focussed EV scenario achieved similar reductions only in the second half of the assessment period, largely due to higher plug-in vehicle shares and zero emissions at point of use. CO_2 emissions reductions were greatest in the combined 'LS EV' scenario, with emissions in 2050 less than half the level of 2012 and 43 % lower than baseline (REF). Lifestyle change makes the achievement of radical carbon reductions such as the 80 % easier, with fewer changes required to the transport or energy system.

We further assessed lifecycle CO_2e emissions (based on GWP100), which include upstream emissions from power generation and fuel production, as well as vehicle manufacture, maintenance and disposal. For the 'lifestyle' (LS) sce-

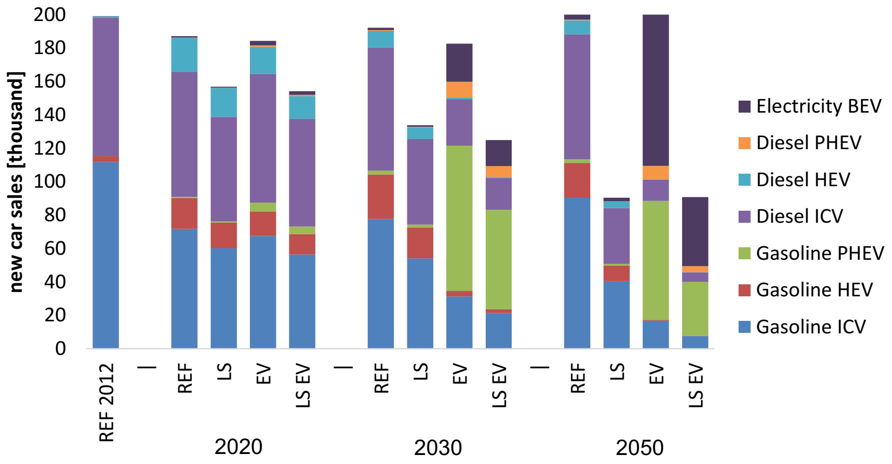

Figure 2. Scenario comparison of new car sales in 2012, 2020, 2030 and 2050. Notes: ICV = internal combustion engine vehicle, HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle.

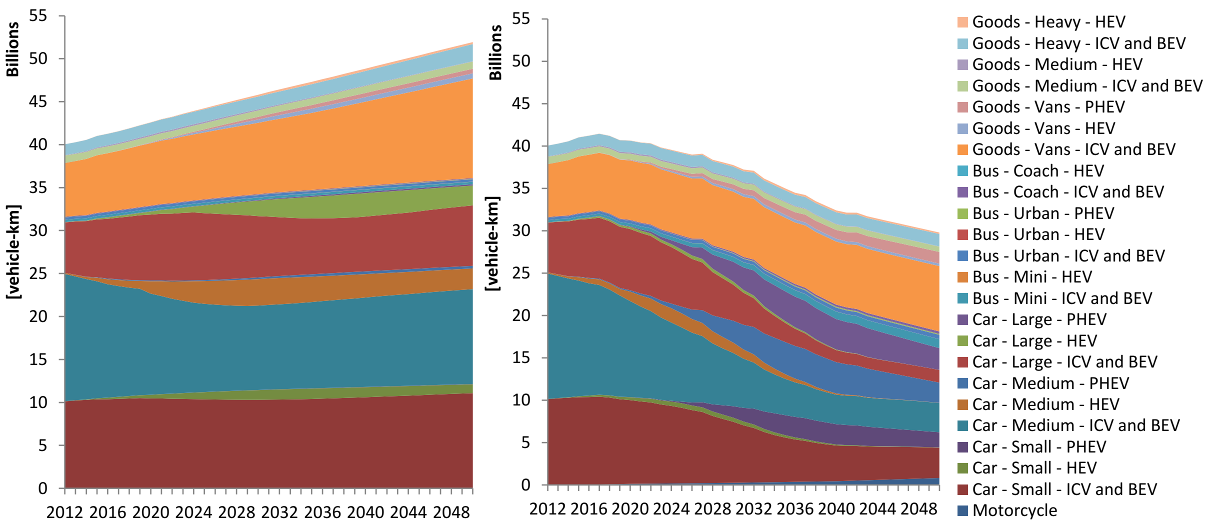

Figure 3. Scenario comparison of road traffic by vehicle type and propulsion system, 'REF' vs. 'LS EV'. Note: Although not shown separately, BEV traffic in the 'LS EV' scenario represents a significant share of the 'ICEV and BEV' totals, particularly for cars and vans.

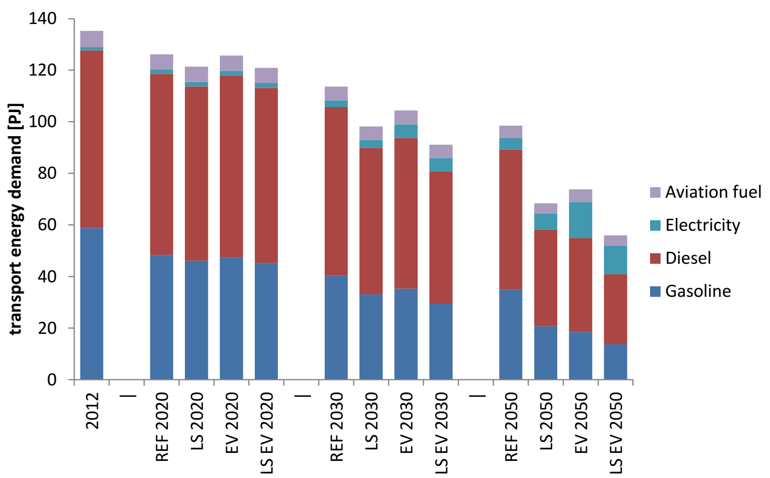

Figure 4. Transport energy demand (in PJ) for the main transport fuels – scenario comparison.

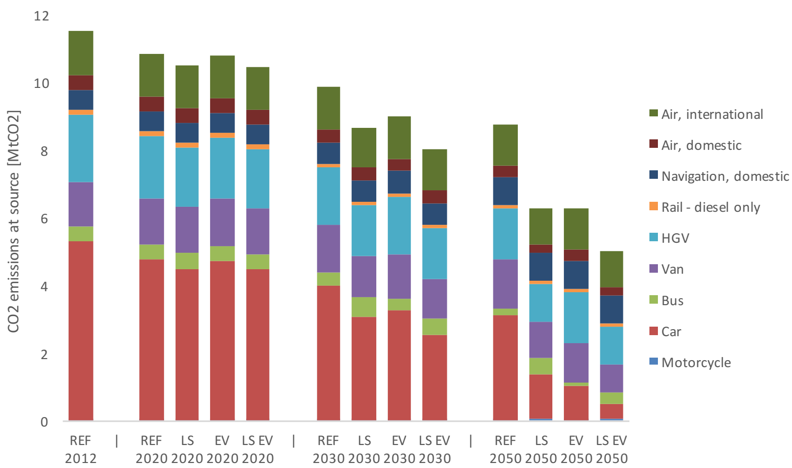

Figure 5. Projections of CO_2 emissions (in Mt) at source from transport in each scenario.

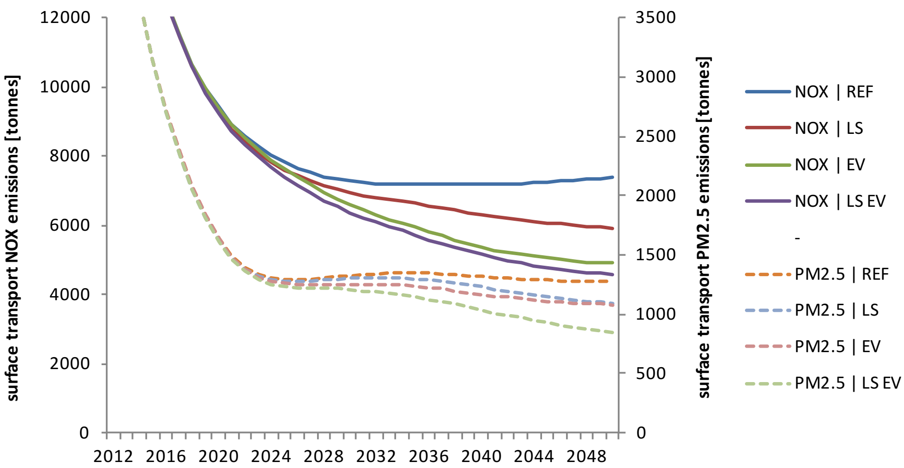

Figure 6. Trends of NO_x and $PM_{2.5}$ emissions in different scenarios.

nario, lifecycle carbon emissions were 14 % (2030) and 31 % (2050) lower than baseline. This could not be matched by the technology-led EV scenario, with reductions of 7 % (2030) and 22 % (2050) compared to baseline. Finally, when looking at cumulative emissions, the combined 'LS EV' scenario unsurprisingly saved the largest amount between 2012 and 2050 (nearly 100 $MtCO_2e$), followed by the lifestyle change (72 $MtCO_2e$) and EV technology-pathway (41 $MtCO_2e$) scenarios. This is due to the lifestyle change scenario reducing demand and therefore emissions earlier as well as the implicit lower indirect emissions from fuel and vehicle production and disposal.

Impact on transport air quality emissions

Strategies designed to promote ULEVs and 'discourage' petrol and diesel sales for road transport in Scotland can have significant impacts on air quality emissions. While following a similar downward trend until the mid 2020s, direct NO_X emissions from all surface transport (road, rail) reduced more in the EV scenario (-9 % by 2030, -34 % by 2050) than in the lifestyle scenario (-4 % by 2030, -20 % by 2050). Direct $PM_{2.5}$ emissions from surface transport decreased more in the first half of the period for the technology-led EV scenario (-5 % by 2030) than in the lifestyle scenario (-2 % by 2030) before showing similar reductions in the second half (-15 % by 2050 for both scenarios). This suggest that in order to reduce the health burden of road and rail traffic pollution the transformation to a cleaner ULEV vehicle fleet may be more effective than demand reductions and radical mode shift.

Discussion and conclusions

There is general consensus that there is a wide variety of possible future levels of energy service demand, end use technology choice and resulting carbon and air quality emissions. Going beyond a more traditional techno-economic driven approach to carbon and air quality emissions mitigation this paper presents results of a socio-technical modelling approach which characterised patterns of travel behaviour consistent with a more sustainable, low energy service demand society and then 'pitched' these against a technology, policy and consumer led high EV pathway. 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 policymakers to consider how to formulate policies that can be robust in the face of such future uncertainty.

The limits set by sub-national policy in Scotland may only be achieved in a radical lifestyle and high EV pathway future (LS EV), as summarised in Table 2. We believe the results are plausible yet they will be very difficult to achieve without a holistic, integrated approach as depicted in the LS EV scenario. Even then, the results suggest that the 80 % climate change target will be very tough to meet without action on heavy goods vehicles, international aviation and shipping (where electrification is problematic). The implications are somewhat different from a predominantly techno-economic driven approach to carbon emissions reduction and present challenges for modelling frameworks which typically rely on encapsulating economically justifiable consumption preferences. 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 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). The newly developed Scottish Transport Energy and Air Pollution Model (STEAM) was used to analyse integrated policy packages that account for the contribution of demand-side and/or supply-side behaviour change measures to meet a stringent 80 % emissions reduction target in Scotland. The model was further used to examine co-benefits of such measures, including reduced use of oil-based fuels and air quality emissions.

The most significant impact of lifestyle change on the wider energy system is due to reductions in the overall demand for final energy, particularly for oil derived fuels. Lower final energy demands bring beneficial effects for energy system costs, carbon emissions and energy import requirements. Lifestyle change alone (without a EV transition) has a similar effect on total final energy demand to a transition to EVs with no lifestyle change. This has important implications for climate mitigation policy. A scenario that involves 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. Of course, the big question is, can it be achieved on this scale and timescale? As described earlier, we have assumed nothing extraordinary by looking at best practice in OECD countries (e.g. 'going Dutch' on active travel in urban areas for certain trip purposes) on trip lengths and trip rates by trip purpose, mode shift and occupancy rates, and ULEV uptake and use. Indeed, the same question might be asked of the rate of progress on technical change. How achievable are, say, significant cost reductions for ULEVs and wide-spread (not just Scotland) investments in charging infrastructures at home and the petrol station network? Given the scarcity of public funds to fuel the technology (r)evolution, who will be delivering this transition? The assumption that encouraging lifestyle change presents more problematic issues for policy makers than techno-centric solutions may is therefore not necessarily correct.

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

Table 2. Summary results of the combined lifestyle and high EV scenario (LS EV).

	2012	2020	2030	2050
Average number of trips (pppa)	1,010	1,006	999	955
Average distance travelled (km pppa)	11,498	11,321	11,029	9,845
Avg. car occupancy	1,57	1,58	1,62	1,76
Mode split (% distance) – cars and motorcycles – slow modes – bus and rail – taxi/'Uber', car clubs, other private – domestic air	 74 % 3 % 14 % 2 % 7 %	 71 % 4 % 15 % 3 % 6 %	 61 % 8 % 19 % 4 % 6 %	 41 % 17 % 28 % 7 % 6 %
'On-road fuel efficiency': – cars, 8 % better per km – vans, 8 % better per km – trucks, 4 % better per km	*km affected* 4 % 2 % 2 %	*km affected* 17 % 17 % 17 %	*km affected* 52 % 59 % 59 %	*km affected* 62 % 70 % 70 %
International air demand growth (pa)	1,2 %	0,9 %	0,5 %	0,1 %
Vehicle technology choice, e.g. share of *new* cars by propulsion/fuel	98 % ICEV petrol/diesel	17 % HEV 1 % BEV 3 % PHEV	2 % HEV 13 % BEV 53 % PHEV	0 % HEV 45 % BEV 40 % PHEV
Direct CO_2, reduction over baseline (REF)	n/a	-4 %	-21 %	-47 %
Lifecycle CO_2e, reduction over baseline (REF)	n/a	-5 %	-20 %	-42 %
Direct NO_X, reductions over baseline (REF)	n/a	-2 %	-12 %	-38 %
Direct $PM_{2.5}$, reductions over baseline (REF)	n/a	-2 %	-9 %	-34 %

more certain. Scottish climate change policy gives more attention to demand-side measures to reduce total kilometres travelled or shift to less carbon intensive modes of transport than the UK or other countries. This paper goes some way to define sustainable (transport) lifestyles and incorporate non-price driven behavioural motivations into our analytical frameworks, therefore improving quantitative assessments of the effectiveness of policy measures and removing our reluctance to adopt them on the basis of 'lack of evidence'.

References

Anable, J. (2005). "'Complacent Car Addicts' or 'Aspiring Environmentalists'? Identifying travel behaviour segments using attitude theory." *Transport Policy* 12 (1): 65–78.

Anable, J., C. Brand, N. Eyre, R. Layberry, N. Bergman, N. Strachan, T. Fawcett and M. Tran (2011). *Energy 2050 – WG1 Energy Demand: Lifestyle and Energy Consumption, Working Paper REF: UKERC/WP/ED/2011/001*. Oxford, UK Energy Research Centre (UKERC), Energy Demand Theme.

Anable, J., C. Brand, M. Tran and N. Eyre (2012). "Modelling transport energy demand: A socio-technical approach." *Energy Policy* 41: 125–138.

Anderton, K. (2012). *Sub-national government responses to reducing the climate impact of cars*. DPhil, University of Oxford.

Brand, C. (2016). "Beyond 'Dieselgate': Implications of unaccounted and future air pollutant emissions and energy use for cars in the United Kingdom." *Energy Policy* 97: 1–12.

Brand, C., J. Anable and M. Tran (2013). "Accelerating the transformation to a low carbon passenger transport system: The role of car purchase taxes, feebates, road taxes and scrappage incentives in the UK." *Transportation Research Part A: Policy and Practice* 49 (0): 132–148.

Brand, C., C. Cluzel and J. Anable (in press). "Modeling plug-in vehicles in a heterogeneous car market using a consumer segmentation approach." *Transportation Research Part A: Policy and Practice*.

Brand, C., C. Cluzel and J. Anable (in press). "Modeling the uptake of plug-in vehicles in a heterogeneous car market using a consumer segmentation approach." *Transportation Research Part A: Policy and Practice*.

Brand, C., M. Tran and J. Anable (2012). "The UK transport carbon model: An integrated life cycle approach to explore low carbon futures." *Energy Policy* 41: 107–124.

CCC (2013). Fourth Carbon Budget Review – technical report, Sectoral analysis of the cost-effective path to the 2050 target. London, Committee on Climate Change (CCC).

CCC (2015). Meeting Carbon Budgets – Progress in reducing the UK's emissions, 2015 Report to Parliament. London, Committee on Climate Change (CCC).

CCC (2016). Meeting Carbon Budgets – Progress in reducing the UK's emissions, 2016 Report to Parliament. London, Committee on Climate Change (CCC).

Chitnis, M. and L. C. Hunt (2012). "What drives the change in UK household energy expenditure and associated CO2 emissions? Implication and forecast to 2020." *Applied Energy* 94 (0): 202–214.

Creutzig, F. (2015). "Evolving Narratives of Low-Carbon Futures in Transportation." *Transport Reviews*: 1–20.

Crompton, T. (2008). *Weathercocks and Signposts. The environmental movement at a crossroads*. London, WWF.

DECC (2014). Updated Energy & Emissions Projections – September 2014, Annex M: Growth assumptions and prices. London, Department of Energy and Climate Change.

DfT (2014). Transport Statistics Great Britain 2014. London, Department for Transport.

European Commission (2005). World Energy Technology Outlook – 2050 (WETO-H2). Luxembourg, European Commission.

Fontes, T. and S. R. Pereira (2014). "Impact assessment of road fleet transitions on emissions: The case study of a medium European size country." *Energy Policy* 72: 175–185.

Fulton, L., P. Cazzola and F. Cuenot (2009). "IEA Mobility Model (MoMo) and its use in the ETP 2008." *Energy Policy* 37 (10): 3758–3768.

Gross, R., P. Heptonstall, J. Anable, P. Greenacre and E4tech (2009). What policies are effective at reducing carbon emissions from surface passenger transport? A review of interventions to encourage behavioural and technological change, ISBN 1 903144 0 7 8. London, UK Energy Research Centre.

Hickman, R. and D. Banister (2007). "Looking over the horizon: Transport and reduced CO_2 emissions in the UK by 2030." *Transport Policy* 14 (5): 377–387.

IEA (2015). *Energy Technology Perspectives 2015: Mobilising Innovation to Accelerate Climate Action*. Paris, OECD/IEA.

Kay, D., N. Hill and D. Newman (2013). *Powering Ahead: The future of low-carbon cars and fuels*. London, Ricardo-AEA for the RAC Foundation and UKPIA.

Kurani, K. S., T. Turrentine and D. Sperling (1994). "Demand for electric vehicles in hybrid households: an exploratory analysis." *Transport Policy* 1 (4): 244–256.

Maione, M., D. Fowler, P. S. Monks, S. Reis, Y. Rudich, M. L. Williams and S. Fuzzi (2016). "Air quality and climate change: Designing new win-win policies for Europe." *Environmental Science & Policy*.

Melo, P. C. (2016). "Driving down road transport CO_2 emissions in Scotland." *International Journal of Sustainable Transportation* 10 (10): 906–916.

ONS (2015). *National Travel Survey: 2015*. London, Office of National Statistics, Department for Transport.

Oxley, T., A. J. Dore, H. ApSimon, J. Hall and M. Kryza (2013). "Modelling future impacts of air pollution using the multi-scale UK Integrated Assessment Model (UKIAM)." *Environment International* 61: 17–35.

Rogan, F., E. Dennehy, H. Daly, M. Howley and B. P. Ó Gallachóir (2011). "Impacts of an emission based private car taxation policy - First year ex-post analysis." *Transportation Research Part A: Policy and Practice* 45 (7): 583–597.

Schafer, A. (1998). "The global demand for motorized mobility." *Transportation Research Part A: Policy and Practice* 32 (6): 455–477.

Schipper, L. (2011). "Automobile use, fuel economy and CO2 emissions in industrialized countries: Encouraging trends through 2008?" *Transport Policy* 18 (2): 358–372.

Scottish Government (2013). *Low Carbon Scotland: Behaviours Framework*. Edinburgh, Scottish Government.

Scottish Government (2013). *Low Carbon Scotland: Meeting our Emissions Reduction Targets 2013-2027. The Second Report on Proposals and Policies*. Edinburgh, Scottish Government.

Scottish Government (2017). *Draft Climate Change Plan – the draft Third Report on Policies and Proposals 2017-2032*. Edinburgh, Scottish Government.

Skippon, S. M., N. Kinnear, L. Lloyd and J. Stannard (2016). "How experience of use influences mass-market drivers' willingness to consider a battery electric vehicle: A randomised controlled trial." *Transportation Research Part A: Policy and Practice* 92: 26–42.

Strachan, N. and R. Kannan (2008). "Hybrid modelling of long-term carbon reduction scenarios for the UK." *Energy Economics* 30 (6): 2947–2963.

Strachan, N., R. Kannan and S. Pye (2008). *Scenarios and Sensitivities on Long-term UK Carbon Reductions using the UK MARKAL and MARKAL-Macro Energy System Models*. London, UK Energy Research Centre (UKERC).

SWOV (2006). SWOV Fact Sheet: Cyclists. The Netherlands, Institute for Road Safety Research.

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

Weber, C. and A. Perrels (2000). "Modelling lifestyle effects on energy demand and related emissions." *Energy Policy* 28 (8): 549–566.

WEC (2007). Transport Technologies and Policy Scenarios to 2050. London, UK, World Energy Council (WEC).