The role of energy demand reduction in achieving net-zero in the UK: Transport and mobility

Christian Brand, DPhil
Transport Studies Unit
University of Oxford and Centre for Research into Energy Demand Solutions
South Parks Road
Oxford, OX1 3QY
United Kingdom
christian.brand@ouce.ox.ac.uk
ORCID ID 0000-0002-1535-5328

Jillian Anable, PhD
Institute for Transport Studies
University of Leeds and Centre for Research into Energy Demand Solutions
34–40 University Road
Leeds LS2 9JT
United Kingdom.
j.l.anable@leeds.ac.uk

Greg Marsden, PhD
Institute for Transport Studies
University of Leeds and Centre for Research into Energy Demand Solutions
34–40 University Road
Leeds LS2 9JT
United Kingdom
g.r.marsden@its.leeds.ac.uk

Keywords
energy demand, mobility, scenarios

Abstract
Decarbonising the transport sector is arguably the most challenging given ever increasing demand for mobility, heavy fossil fuel use, reliance on carbon-intensive infrastructure, and deeply embedded car-dependent lifestyles. Aviation, shipping and heavy goods transport are hard to decarbonise because realistic zero carbon technologies are limited for longer distances. This paper investigates the contribution energy demand reduction in the transport sector could make to climate mitigation efforts. Here we use a bottom-up modelling framework that comprehensively estimates the potential for mobility-related energy demand reduction at a country level. Replicable for other countries, our framework is applied to the case of the UK where we find that reductions in mobility energy demand of up to 61 % by 2050 compared with baseline levels are possible without compromising on citizens' quality of life. This translates to total lifecycle carbon emissions reductions of up to 72 % by 2050 compared to 2020 levels, with about half of the reduction coming from mode shifting and avoiding travel and moving goods. The other half comes from vehicle energy efficiency and electrification as well as downsizing of the vehicle fleets. Our findings show that energy demand reduction in the transport sector can make it easier to meet sectoral carbon budgets and reduce reliance on more drastic car use restrictions further down the line. There are big potential co-benefits from reducing energy demand as we avoid unnecessary travel, become more multi-modal and electrify a smaller vehicle fleet. Active travel and less air pollution from burning fossil fuel will all improve health. Reducing energy demand may also lower household travel bills, reduce business costs, improve energy security, and transform the job market away from the incumbent fossil fuel economy.

Introduction
One of the biggest oversights in the transport decarbonisation debate is the role of energy. The sector is 95 % dependent on oil and accounts for 21 % of global carbon emissions (IEA, 2021b). It is now the largest emitting sector in many developed countries (IEA, 2021b). While Europe and North America dominate historic transport emissions, much of the projected growth in emissions is in Asia.

Of course, if we replace every fossil fuel mile driven with a mile driven by a vehicle powered by 100 % renewable energy resources then we could (ignoring materials) claim to have reached a zero carbon future. But as we switch demands which were previously not electrical we implicitly require more generation and more storage (EEA, 2018; IEA, 2021a). This could put strains on our power networks and risk overloading grids unless we plan for it and invest accordingly. So the quantum of demand for electricity matters. And that's just cars – air travel and heavy goods transport can only be partially electrified. And it matters more when we lift our gaze from transport to all of the other sectors in the economy that are making the same switch, such as domestic heat. The multiple demands for additional electricity, if left unchecked, could require an electricity system four times the size it is today (IEA, 2021b).

Scaling up grid provision is technically feasible, but is it sensible? It makes the economy more reliant on one energy system with associated resilience challenges and it raises serious equity issues. Are the 25 % of households that do not own cars in the UK, for example, expected to pay in to allow vehicle owners to plug in their vehicles? It has even been suggested that car owners with smart chargers will have access to lower energy tariffs as this will improve storage capacity for the grid and reduce overall costs. Is that fair? Overall costs are only reduced from some imagined future which is created by the reliance on more electric vehicles (EVs), not from today's levels.

But of course, transport planners have long been arguing that other than at the tailpipe a car is a car is a car, however it is propelled (Anable, 2021). Electrification does not tackle congestion, exclusion, physical inactivity, particulates from brakes and road safety etc. Whilst air quality and climate emissions will diminish as problems, cheaper motoring could well bring others.

So what then? This paper addresses the issue of how much energy we need for everyday mobility and what the carbon implications of different futures might be. The question at the heart of the paper is familiar: how far can improvements in transport energy efficiency and the carbon content of energy via technological improvements help us reach our carbon goals without any reductions in the demand for the energy service – mobility – itself? Using the UK as a case study, it will not come as a surprise that the paper finds what some others have done before (Anable and Goodwin, 2019; CCC, 2019; Pye et al., 2017; OECD/ITF, 2021a), that the country will find it very difficult to reach its 2030 or 2050 carbon targets without significant energy demand shift. The main contribution of this study, though, is that it has dared to go beyond quantification of 'what' has to happen in terms of the balance between avoiding, shifting and improving energy service demands by detailing both the 'how' as well as the wider costs and benefits.

The almost universal focus on *improving* energy consumption per passenger-km or tonne-km travelled ignores the other two core elements of the **Avoid-Shift-Improve hierarchy** (Schipper and Marie-Liliu, 1999; EEA, 2011; Gota et al., 2019) of *avoiding* travel in the first place (trip reduction due to change in activity) and *shifting* travel to more sustainable modes (reduction in energy use per passenger-km or tonne-km travelled). This hierarchy has been used extensively in the past, including in the analysis of climate mitigation options in transport for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Sims et al., 2014). Here it has been used to emphasise the priority ordering and layering of our scenarios that stand apart from the dominant supply and vehicle technology-oriented approach to energy reduction and decarbonisation in the sector. Our two "low energy demand" (LED) scenarios, called ***High Ambition (HA)*** and ***Transformative Change (TC)***, reinforce the growing consensus that relying on technical solutions alone is insufficiently rapid and risky, and that policies influencing the demand for travel and mode switching should have a more prominent role (CCC, 2019; IEA, 2021b). Here the demand for the mobility itself (i.e. the distances travelled and the travel modes used) will be at least as crucial to future energy demands as the fuel types and real-world efficiencies of the vehicles.

We started the development of our scenarios by exploring what could possibly be achieved with existing technologies and current social and political framings. We pushed ourselves to think about what felt like feasible shifts in terms of the number of journeys we make and the distances travelled for different journey purposes by mode. For example, where international holidays reduced we had to make allowances for more and longer domestic leisure journeys. Different policy levers were assumed such as frequent flyer levies and increasing taxation on multi-car household ownership along with the usual carrots of road space reallocation and better provision for walking, cycling and other forms of zero carbon, active travel. Significant freight consolidation, improved load factors and better on-road fuel efficiency was also required. Electrification remains central but with fewer and smaller vehicles which are more intensively used.

Here we set out quite how far our ambitions have been able to push the energy and carbon envelope for mobility. However, what is different about this scenario exercise is that it creates an upbeat vision for what a lower energy demand life could look like. It means doing things differently and quite radically so, but it is a positive view of how we can still live a good life doing the things we need and enjoy with overall lower costs to society as a whole (Vogel et al., 2021). People can still have access to local services, leisure and holiday activities, and diverse employment opportunities, but they will do so breathing cleaner air and with better mental and physical health to boost.

Why we need to talk about energy for mobility

As economies and populations grow, demand for goods grows, as does the number of people with the desire and means to travel. Globally, total transport activity is expected to more than double by 2050 compared with 2015 under the trajectory reflecting current efforts (OECD/ITF, 2021a). Any technological advances in decarbonising transport would simply be more than offset by increased demand for mobility. This has led many to believe that there is no way we can meet the decarbonisation targets of the Paris agreement by 2050 without reducing demand to more sustainable levels (OECD/ITF, 2021a). But this is hard to do. It requires the transformation of the whole transport system, including tackling how often and how far we travel and move goods. Some of the more promising options, such as road-space reallocation (Aldred and Goodman, 2020) and higher fossil fuel taxes (Lam and Mercure, 2021) have met resistance.

The (near) total dependence on oil across all forms of passenger and freight transport is hard to change – and even harder to change fast (EEA, 2020). Substituting oil with low carbon fuels, such as electricity, will drastically reduce emissions by 2050. But even an optimistic scenario where global new car sales were 60 % electric by the end of the decade would see CO_2 emissions from cars drop by only 14 % by 2030 compared with 2018 (IEA, 2021c).

In the UK, road transport accounted for just under three quarters of transport energy consumption in the UK in 2017, with the remainder almost entirely from air travel (23 %) (BEIS, 2019). Of the road component, energy use from cars accounts for more than half (60 %), with most of the remainder coming from 'light duty vehicles' (vans) (16 %), heavy goods vehicles (HGVs) (17 %) and buses (3 %). Energy use from transport has increased by 16 % since 1990 (6 % since 2013) against a UK economy-wide *decrease* of 4 % (CCC, 2018; BEIS, 2019) and remains 98 % dependent on fossil fuels. It has grown as a share of overall carbon emissions with no net reduction between 1990 and 2017 (*vis-à-vis* –43 % for all sectors combined). The current approach to decarbonising transport in the UK could see a 28 % increase in car ownership, with 10 million more cars on the road by 2050, requiring serious questions about the resources to construct these 43.6 million vehicles and providing even more land and street space used for car parking (Frost et al., 2021).

The primary focus of UK policy has been to change the vehicle fleet from petrol and diesel, first to Ultra Low Emission Vehicles (ULEVs), and then to zero-emission vehicles (ZEVs)[1], primarily through electrification. A lack of progress with heavy goods vehicles and aviation persists, but the unexpected change is the increase in new car energy consumption and CO_2 (SMMT, 2018). Switching from diesel accounts for a small proportion of this increase; the main culprit is a continued swing towards larger passenger cars, particularly Sports Utility Vehicles (SUV), which use about 15 % more energy than their hatchback or sedan equivalents. Electric vehicles accounted for 8.8 % of sales in 2020 (SMMT, 2020) (up from 2.5 % in 2019), with two out of five sold being plug-in hybrid electric vehicles (PHEVs). PHEVs have shown to perform little better in terms of energy use and carbon emissions than the most efficient conventional ICE vehicles in real world conditions, as they have been shown to operate in electric mode for only a third of the miles travelled (Plötz et al., 2020). This gap between declared vehicle performance and real-world results prevails across all vehicle types and technologies. For new cars, fleet average test cycle data suggest a 30 % reduction in tailpipe CO_2 since 2000. In practice, there has only been an estimated 9 % reduction in tailpipe emissions in real-world conditions, and only 4 % since 2010. The 'performance gap' between official and real-world values grew over time, peaking at 40 % in 2016 (NEDC test cycle). This gap has effectively negated any reported savings from efficiency improvements over the past decade.

The COP26 presidency programme focused entirely on road-transport electrification (UK Government, 2021). Yet life-cycle emissions from electric vehicles depend heavily on the kind of electricity, battery and materials used. Globally, uptake has been slow apart from a few leaders, such as Norway, which has thrown everything at the transition. Even if all new cars were electric from today, it would still take 15–20 years to replace the world's fossil fuel cars (Keith et al., 2019). Electric cars do not solve problems of road traffic congestion, safety and other issues of car dependency (OECD/ITF, 2021b). They also need a reliable electricity supply – not a given in many parts of the world – and do not address transport inequality and social injustice within and between countries (Frost et al., 2021), especially in the developing world where e-cars may well only be an option for the powerful and wealthy.

A collective sense of entitlement and dislike of limiting "personal choice" have a lot to do with inaction on reducing and improving travel by powered vehicles. Many people are reluctant to give up their car (RAC, 2021; Große et al., 2018; OECD/ITF, 2021b) or fly less (Cohen et al., 2013), feeling that it is an infringement of their rights. Efforts to decarbonise transport are being hindered by a cultural attachment to the polluting status quo, which isn't as present in other sectors (William et al., 2021).

1. ULEVs produce <75 g/km CO_2 under the existing test cycle and includes pure Battery electric vehicles (BEVs), Plug-in hybrid electric vehicles (PHEVs). Zero emission vehicles emit no carbon or pollution from the tailpipe and include BEVs and Fuel cell vehicles. Strictly these are only zero emission when powered by renewable or zero emission electricity (DfT (2018a) op. cit.)

Scenario building and modelling approach

This section outlines the scenario and modelling approach that we adopted to construct our low energy demand (LED) scenarios. The first section outlines how we created a scenario narrative and devised coherent scenarios for transport and mobility. The second section describes the bottom-up transport energy demand modelling used for two low energy demand scenarios.

SCENARIO BUILDING

Our scenario approach is attempting to give insights into the possible scale of change in energy demand and greenhouse gas (GHG) emissions under certain circumstances. Considerable effort has been made to ensure that the scenarios are internally consistent. We have developed three scenarios, which include:

1. BAU – Business-As-Usual: Identifies levels of energy demand for mobility up to 2050 based on current known and planned UK Government policy instruments. Notably, policy ambitions without actionable measures are excluded.
2. HA – High Ambition: Assumes significant shift in the attention given to transport and energy demand strategies providing an ambitious programme of interventions across the whole transport sector describing what could possibly be achieved with existing technologies and current social and political framings.
3. TC – Transformative Change: Considers transformative change in technologies, social practices, infrastructure and institutions to deliver both reductions in energy but also numerous co-benefits such as health, improved local environments, improved work practices, reduced investment needs, and lower cumulative GHG emissions.

As strategies to **avoid travel demand and car ownership**, we consider ways to 'lock-in' recent demand changes, some of which started well before the Covid-19 pandemic, new regulatory frameworks to steer emergent transport innovations, the promotion of 'car clubs' (Wilson et al., 2018) and freight consolidation centres (Cherrett et al., 2012), and coordination of transport and planning objectives to reduce the need to travel people (e.g. tele-shopping) and goods (e.g. localisation of food shopping). For each of these measures we assessed the likely effects on trip rates for different journey purposes and trip lengths in the medium (2030) and longer (2050) term.

National and international examples of sustained lower car dependent lifestyles indicate that this can be achieved at least in some localities. Such a prospect puts much greater emphasis on policies which influence and provide for more energy conserving lifestyles, including: emerging models of car 'usership', changing social norms around mobility, new spatial patterns of population growth, the changing nature and location of work, education, housing, healthcare and leisure, reconfiguration of travel by digital technology, and new ways of paying for road use or energy (electricity). This happens predominantly in urban areas.

Policies such as car clubs, smart ticketing, investment in rail and in digital technology have shown to reduce travel demand and car ownership in some groups, and the scenarios extend the behaviours to other groups of society. Having access to and using a shared vehicle has been shown to lead to reductions in personal car ownership and miles driven, as well as increased use of other modes of transport (Marsden et al., 2018; Ceccato and Diana, 2021). This reduction includes households giving up a car completely, but equally important is reducing from, say, two cars to one car. Support options in a LED world take the form of both carrots (e.g. supporting interoperable underpinning ICT infrastructure, 'smart' design of car scrappage, integrating shared travel into multi-modal journey-planning apps, providing dedicated car parking, charging and signage to car club vehicles) and sticks (e.g. parking charges and restrictions in residential areas and workplaces for privately owned vehicles). Access to subsidised or free public transport is at present largely determined by age, and it is clear that behaviour patterns also show strong age effects but making best use of this may justify an overall review of age boundaries both for the young and old. Improving the experience for these sub-groups of living without a car should not only improve the chances of them opting to live without one (or with fewer per household than they might have done) for longer, but will simultaneously improve non-car travel for a wider set of people and places.

To avoid 'induced travel' from emerging innovations (Fulton, 2018) such as mobility as a service (MaaS), autonomous and connected vehicles (ACV) and artificial intelligence (AI), we assume a 'preventative' regulatory framework designed to ensure these innovations result in a net increase in co-benefits such as social inclusion and transport and energy system flexibility is in place. Specific interventions such as mandating the use of autonomous vehicles in shared contexts, public investment in car-clubs or MaaS in rural areas and designing car scrappage schemes to accelerate the uptake of mobility packages as opposed to new vehicles, are necessary and key parts of the LED scenario mix.

Enabling travel avoidance is chiefly a matter of coordination of planning and transport objectives in the housing type and location, density of development and location. It involves innovation at workplaces, as well as the timing and management of access to services (including schools and healthcare). Often considered longer term options, the recent demand changes due to Covid-19 have shown that travel avoidance can happen fast, further and more flexibly now. Finally, the LED scenarios assume a stop to new road building because travel demand falls – instead, existing roads are maintained and repurposed when it makes sense to do so, e.g. low traffic neighbourhoods and 'superblocks' (Mueller et al., 2020).

As strategies to **shift travel to the most sustainable modes**, we consider systematic support for the very lowest energy modes of transport and restraint for the highest energy modes. This is supported by a new approach to prices and taxes to reflect a fuller range of costs and benefits.

Enabling and encouraging a shift from private motorised travel to more energy efficient modes requires systematic support for the very lowest energy methods of transport – walking, cycling (including e-bikes and e-scooters) and public transport, through investment programmes on both capital and revenue spending, priority use of road space, an expansion of 'soft' or 'smarter' methods of encouraging behavioural change. The strategic goal is to design "a mobility system where it is more normal to take part in activities using the most sustainable modes more of the time" (Marsden et al., 2016). The new approach to transport pricing would ensure that the relative prices of different transport options reflect the full range of costs and benefits to the consumer, including health, energy, embedded emissions, congestion and other environmental impacts. Restructuring prices include direct subsidy to lock in sustainable travel choices by charging for use of scarce resources at a rising unit rate where more is used. Such pricing mechanisms would therefore expand the traditional notion of road user charging to reflect wider transport and energy system usage and will incorporate thinking on how to avoid increases in demand that may be stimulated by lower motoring costs of electric vehicles.

As strategies to **improve the efficiencies of individual modes**, we consider improving the efficiency of vehicles in use, particularly through increased occupancy (esp. for commuting and business travel), restructuring targets for the uptake of zero emission vehicles to include 'phasing out' hybrid electric vehicles by 2030 (HA) and 2025 (TC), and regulation to mandate the uptake of the most efficient and cleanest vehicles in their class.

While a comprehensive and sustained eco-driving programme (as in the Netherlands) is part of the LED scenario mix, a focus on efficiency of vehicles in use is much more than that. It considers maximising assets in ways that substantially reduces single car occupancy and individual ownership. There is no detectable policy weight placed on the efficiency of vehicles 'in use' even though increasing vehicle occupancy, potentially through mobility sharing platforms, would ratchet down energy intensity of travel considerably. There are a number of potential types of initiative targeting both businesses and individuals, again falling into 'carrot' (mileage fee reimbursement rates and salary sacrifice incentives) and 'stick' (regulation of the use of own cars on business travel, parking restrictions and fees) as well as a review of company carbon accounting to incorporate commuting travel. Much of the evidence now suggests that the trajectory for urgent CO_2 savings to achieve 'net zero' requires phasing out all forms of conventionally fuelled internal combustion engine (ICE) and hybrid electric vehicle (HEV) cars and vans by 2030 (Brand et al., 2020; CCC, 2019). Furthermore, to counter the trend towards ownership and use of larger cars, the LED scenarios involve regulating to phase out the largest vehicles in advance of the above 'phase-out' target or restrict their use to genuinely appropriate circumstances.

MODELLING LOW ENERGY DEMAND FUTURES

Low energy demand within the transport-energy system was modelled using an established modelling tool suitable for policy analysis, the Transport Energy and Air pollution Model for the UK (TEAM-UK) (Brand et al., 2019b). To date, the underlying transport-energy-environment system modelling framework has been applied in a number of prospective scenario (Anable et al., 2012; Brand et al., 2017; Brand et al., 2019a; Brand et al., 2020) and policy (Brand et al., 2013) modelling studies.

The transport demand model simulates passenger travel demand as a function of key travel indicators structured around data obtained from the UK National Travel Survey (DfT, 2016), including the average number of trips and average distance travelled per person per year. These were further disaggregated by **eight main trip purposes** (commuting, business, long distance leisure, local leisure, school/education, shopping, personal business, other), **eight trip lengths** (Under 1 mile, 1–2 miles, 2–5 miles, 5–10 miles, 10–25 miles, 25–50 miles, 50–100 miles, and More than 100 miles) and **twelve modes of passenger transport** (walk, bicycle, car/van driver, car/van passenger, motorcycle, local bus, coach, rail and underground, other private, taxi, domestic air, other public). International air travel is modelled separately as a function of income (GDP/capita), population and supply and policy costs. Freight demand is simulated as a function of economic activity (GDP/capita), population and freight transport prices, with reference demand elasticities taken from a RAND Europe study (Dunkerley et al., 2014). For the LED scenarios, these elasticities were assumed to change dynamically to simulate structural changes in the economy and partial decoupling of freight demand from economic activity.

The vehicle fleet turnover model provides projections of how vehicle technologies evolve over time for 1,246 vehicle technology categories, including 283 car and 566 van[2] technologies such as increasingly efficient gasoline internal combustion vehicles (ICV), battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and hydrogen (H_2) fuel cell electric vehicles (FCEV). The car and van fleet models are the most detailed, including market (private vs. fleet/company, three car sizes/segments, six van types) and consumer segmentation (four private and two fleet/company segments for cars, two segments for vans). The heavy goods vehicle (HGV) model is somewhat simpler and includes diesel ICV, diesel P/HEV, BEV and hydrogen FCEV drivetrains – power-to-liquid (e-fuels) and overhead catenaries for BEV or PHEV only play a minor role given limited appetite in the UK market to develop and invest in these technologies (Ricardo, 2019). New vehicle choice is modelled using a hybrid discrete choice and consumer segmentation model, as described in Brand et al. (2017; Brand et al., 2019b). Vehicle scrappage probabilities[3] were left unchanged, so that the mean car age remained at about 7 years, and 6.5 years for vans (see Brand et al., 2019b for methods). Total car ownership is modelled based on established methods (Whelan, 2007; DfT, 2013) taking into account disposable household incomes, average vehicle costs, household location (urban, rural), public transport availability and car ownership saturation rates for multiple car ownership.

To develop the LED scenarios we applied the socio-technical and policy factors mentioned earlier (see storylines) to each element of each journey purpose to calculate total changes in demand by each mode by 2030 and 2050. We also made a raft of additional assumptions and calculations about vehicle technology supply and regulatory constraints, and factors underlying the scale and speed of fleet evolution. Key assumptions for both LED scenarios include:

- No more substantial new road building or airport capacity expansion; some roads repurposed for shared, public and active mobility. No more development on greenfield sites;
- Integrated transport authorities in all city regions, covering urban mobility (One network; One timetable; One ticket);
- Doubling investment in public transport, walking and cycling with the construction of high-quality cycling networks of segregated cycleways in all urban areas;
- Single occupancy car use becoming socially unacceptable. Parking charges and infrastructure designed to prioritise vehicle sharing (car club spaces, etc.). High taxation on more than one car per household;
- Eco-levy applied to the 'whole' system – the more you travel and the more polluting modes you use, the more you pay – includes air travel (frequent flier levy);
- Car fleet increases initially but is then gradually reduced (vis-à-vis an increase in the BAU case) as car ownership is becoming socially unacceptable, particularly amongst the 16–25 year olds. Driving licence uptake is down with transition to 'car usership' (shared use, ride pooling);
- But taxi and shared fleets increase – all electric by 2030;
- Increase in van (light commercial vehicle) fleet due to more online shopping – electric only from 2030;
- Large and heavy ICE, PHEV and HEV cars gradually phased out by 2030 and a substantially expanded bus fleet will be largely electric. Big investment in and standardisation of charging infrastructure;
- HGV/trucks – renewed push for consolidation centres around big cities and towns – maximising use of brownfield sites to do so;
- Road freight – improved logistics, vertical integration e.g. Amazon – assumed a 20 % improvement in average load factors (from 0.5 to 0.6 by 2030) for long and medium distance freight;
- Relatively small shifts from road to rail freight, as rail capacity is largely taken up by net passenger rail increases (leisure up more than commuting and business down). UK rail freight remains inelastic.

Additional measures and assumptions specific to the *Transformative Change* scenario include:

- The phase out of ICE, PHEV and HEV cars is brought forward to 2025, so no cars are sold after 2025 that include an internal combustion engine;
- Less demand for domestic and international aviation driven by an increased public awareness of the environmental damage, higher costs for frequent flying, and increased fuel costs through taxation. As a result, aviation demand in 2030 is about 30 % lower than pre-pandemic levels;
- Introduction of a four-day working week (Haraldsson and Kellam, 2021), particularly in the service sector, due to a greater focus on quality of life (Gash et al., 2012), resulting in a 10 % reduction in commuting trips per person by 2030 and further reductions by 2050;

2. Vans = light commercial vehicles up to 3.5t gross vehicle weight, including panel & side vans, car derived vans, pickup & 4x4 vans, drop & tipper vans, box, Luton & insulated vans, and 'other' vans (campervans, etc.).

3. The UK car fleet age profile implied a 50 % scrappage probability applied for cars that were ~16 years old.

- Increased reduction in commuting due to working at home or teleworking where industrial restructuring allows greater flexibility;
- Greater reliance on video-conferencing in businesses improving work-life balance;
- Even lower car ownership levels, particularly in urban areas, in line with the assumptions reducing the need to travel and a shift towards public transport, e-micro mobility and shared mobility.

A more detailed set of assumptions and the supporting evidence are provided in Brand et al. (2021a).

Findings

THE UK CAN MORE THAN HALVE ENERGY DEMAND FOR MOBILITY RELATIVE TO CURRENT LEVELS

The higher uptake of lower and zero carbon vehicles combined with efficiency gains, mode shifts and significant alterations to work, leisure and shopping travel patterns resulted in final energy demand being more than halved from this sector by 2050 compared to the 'business-as-usual' scenario (BAU) (Figure 1). The combined effects of 'avoiding' and 'shifting' demand provided more than half of this reduction, particularly early on (Figure 2), with the other half coming from 'improving' demand through electrification, eco-driving, speed limits and improved vehicle occupancy rates and freight load factors. In a lower energy demand world we would see early gains being made in the 2020s so that energy demand were 27 % (high ambition) and 43 % (transformative) lower than BAU already by 2030. Demand for conventional fossil fuels (gasoline, diesel) was up to 50 % lower by 2030, and up to 80 % lower by 2050, while demand for electricity grew steeply, rising from its 2015 base of just 15 PJ (1 % of total, largely for rail) to around 50 % of energy demand (242 PJ in 'high ambition') by 2050 in the low energy demand scenarios.

LOWERING TRANSPORT ENERGY DEMAND MAKES INCREASED CLIMATE AMBITION POSSIBLE

The low energy demand scenarios resulted in deep cuts in direct (i.e., tailpipe, at source) carbon emissions from transport – with earlier gains in the 2020s when compared to a scenario focussed only on efficiency and electrification. Direct CO_2 emissions were up to 54 % (2030, transformative) and 80 % (2050, transformative) lower than in 2020 (Figure 3). This was largely due to reductions from direct (tailpipe) emissions from cars, which were offset by modest increases in bus, rail, shared mobility and motorcycle emissions due to significant mode shift away from private car use. Lower energy demand thus makes the achievement of mid-term carbon budgets and longer term 'net zero' targets easier, with fewer changes required to the transport or energy system.

The TEAM framework allowed us to further assess lifecycle CO_2-eq emissions, which include the above direct emissions as well as indirect emissions from power generation and fuel production, as well as vehicle manufacture, maintenance and disposal (for methods and data, see Brand et al., 2019b). By 2030, lifecycle carbon emissions from domestic transport were 35 % (HA) and 48 % (TC) lower than in 2020 – a marked change to the BAU case (11 % lower in 2030 than in 2020). By 2050, lifecycle emissions were 69 % (HA) and 72 % (TC) lower than in 2020 – again a marked improvement to a 25 % reduction in the BAU case.

Finally, when looking at cumulative emissions of the period between 2020 and 2050, the low energy demand scenarios had 34 % (HA) and 43 % (TC) lower emissions totals than the BAU case. In a transformative world, cumulative emissions from domestic transport were 2.4 $GtCO_2$-eq compared to 4.3 Gt in the BAU case. This large reduction was due to the earlier gains from

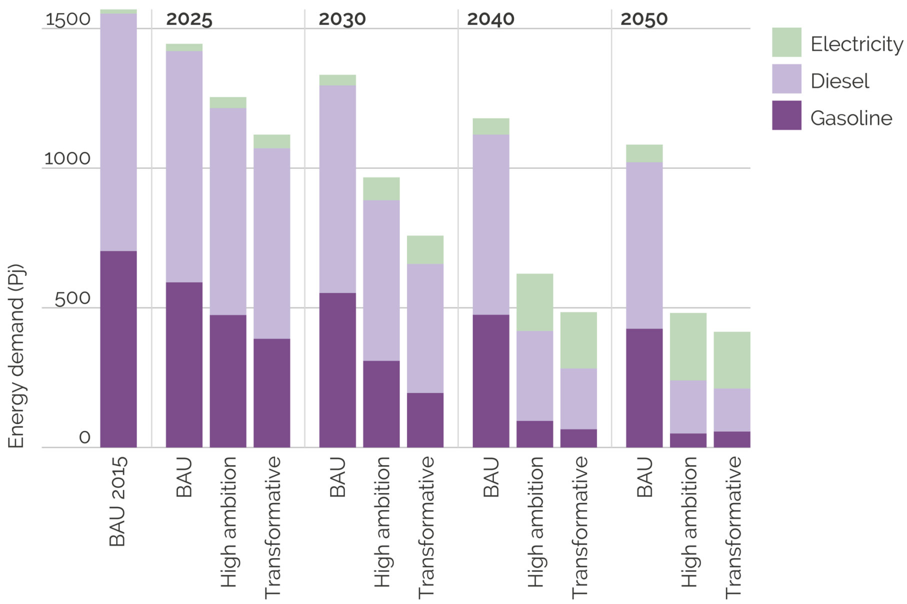

Figure 1. Energy use by mode and fuel – transport by road and rail.

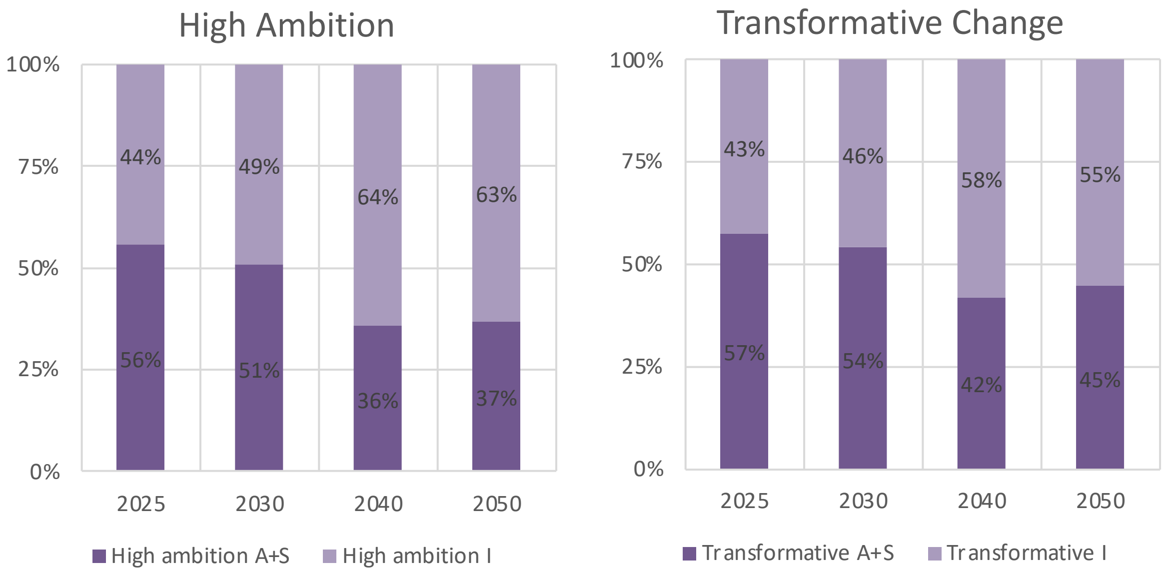

Figure 2. Contributions of Avoid+Shift (A+S) and Improve (I) components to transport energy reduction (road and rail only). Left panel: High Ambition scenario, Right panel: Transformative Change scenario.

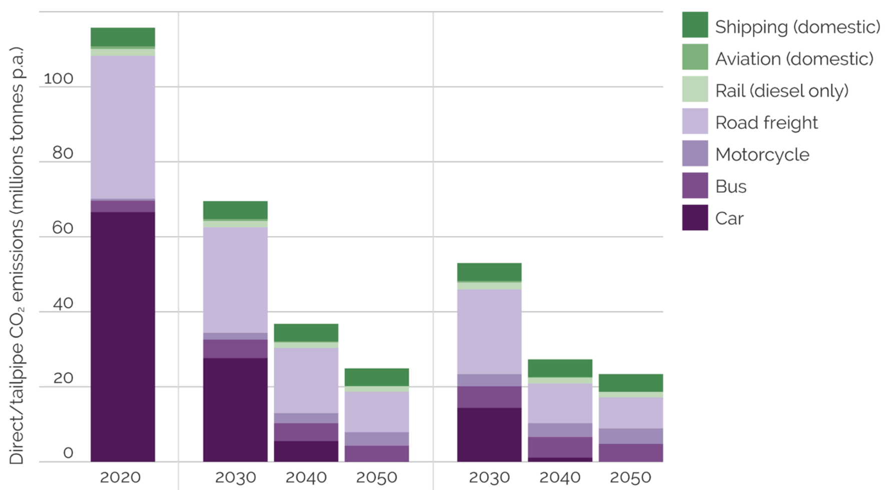

Figure 3. Direct CO_2 emissions (domestic transport, excluding international aviation/shipping).

changes in travel patterns in the 2020s as well as the implicit lower indirect emissions from fuel and vehicle production and disposal of a smaller vehicle fleet.

TRAVEL DEMAND SHIFTS IN A LOW ENERGY DEMAND FUTURE

'Avoid + Shift': the changing surface passenger travel patterns

The low energy demand scenarios gave large reductions in distance travelled by car as a driver and a passenger of up to 55 % when compared to the current levels (Figure 4). This was on the back of only small changes to total distance travelled per person, from about 6,600 miles a year in 2017 to about 6,300 (high ambition) and 5,800 (transformative) miles per person per year in 2050.

At the same time, ride sharing (e.g. Uber, Lyft), car clubs and more shared use of the existing fleet resulted in occupancy rates to increase from current level of about 1.6 people per car to 1.9 (high ambition) and 2.1 (transformative), which was largely due to increases in occupancy for leisure, commuting and school travel (with changes to business travel somewhat limited). People in a LED UK become progressively more 'multi-modal' and less car dependent, particularly in urban areas (Figure 5). The reduction in car travel comes about because of significant mode shifts, particularly to urban bus travel and regional, suburban rail towards the latter part of the period. Mode shift is combined with destination shifting as trips are either totally abstracted from the system through virtual or shorter travel because of localisation and working in local hubs (and pubs, occasionally) rather than central HQs. By 2030, the car is still used for the majority of distance travelled either as a driver or passenger, but this drops to 49 % (high ambition) and 40 % (transformative) of distance travelled per capita by 2050. Using

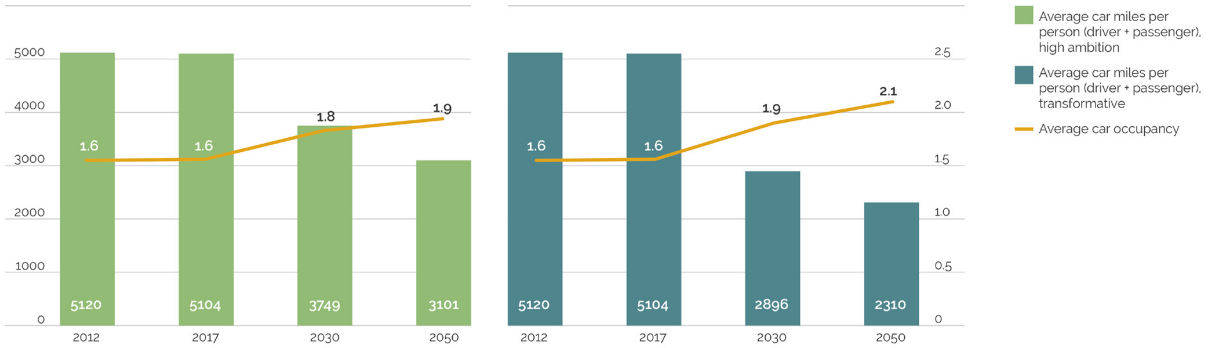

Figure 4. Change in average per capita car miles + average car occupancy. Left panel: high ambition, right: transformative.

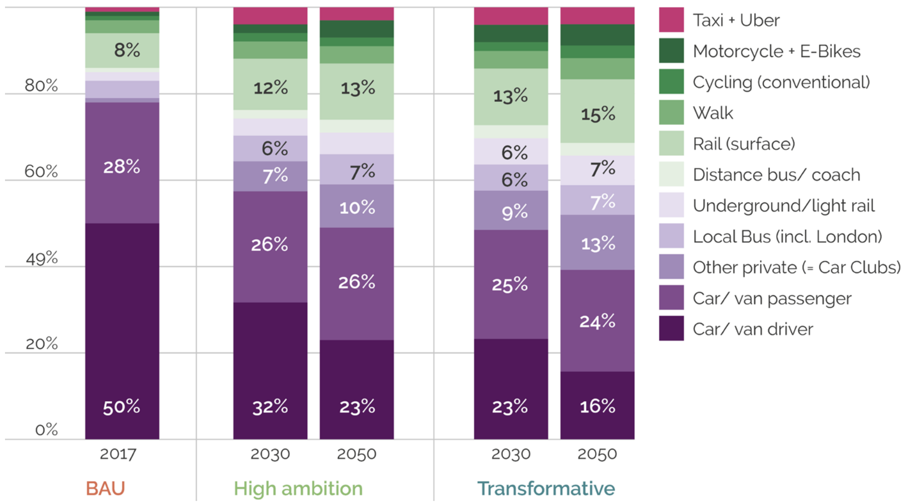

Figure 5. Change in trip mode shares (by trip distance) across all trip purposes.

a car club vehicle becomes much more prevalent, from a small base to almost 13 % of miles travelled by 2050. At the same time, 'active travel' (walking, cycling and e-biking) increases from a low base of less than 2 % to more than 11 % of distance travelled, mainly replacing urban car trips of under 8 km in length, while also increasingly substituting longer suburban and even rural car trips by e-bike. While this surpasses levels seen today in countries with similar weather and topography and regarded as demonstrating best practice in this area – e.g. the Netherlands, Denmark, and some cities in Germany – it is well within the realms of plausibility (Brand et al., 2021b; Brand et al., 2021c) and most people's capability (Philips et al., 2022). Implicit in the assumptions made here is the fact that private cars are increasingly banned or priced out of urban areas.

Air travel

Growth in domestic flights saturated and then declined due to growing unacceptability of flying short distances and increased prices leading to increasing use of high speed rail (assuming HS2 will be operational by the 2030s), a rejuvenated interurban rail network and express coaches. Domestic air-miles in the low energy demand scenarios were thus up to 22 % and 39 % lower in 2030 and 2050 respectively than in 2020. Taking into account expected longer term effects of the Covid-19 pandemic on business and leisure air travel, higher prices (e.g., frequent flier levy) and social 'unacceptability' of flying longer distances, air-miles in the low energy demand futures are up to 27 % (high ambition) and 46 % (transformative) lower in 2050 than in the BAU case.

Freight transport

Fuelled by the move towards a service economy and more teleshopping in a low energy demand future, van ownership and use continue to increase as they did in the decade prior to 2020. Van-km decreased somewhat due to improvements in van technology and urban delivery logistics. Town/city centres increasingly ban heavy goods vehicles but allow electric e-cargo bikes and vans, and local traffic regulations will give priority to professional home delivery, centralised parcel lockers close to the homes, and consolidated urban distribution with clean vehicles. As a result, the overall distance travelled by vans still increased, but 'only' by 23 % in 2050 over 2020 levels – which is less than the 69 % increase depicted in the BAU case. Heavy goods vehicles are still set to grow due to economic and population growth. However, mainly as a result of increased load factors through business-led vehicle utilization measures and consolidation centres, overall distance travelled by these vehicles will be lower than BAU and about the same in 2050 as the 2020 levels in the transformative case. Rail and waterborne freight play a bigger role, mainly due to mode shift from roads.

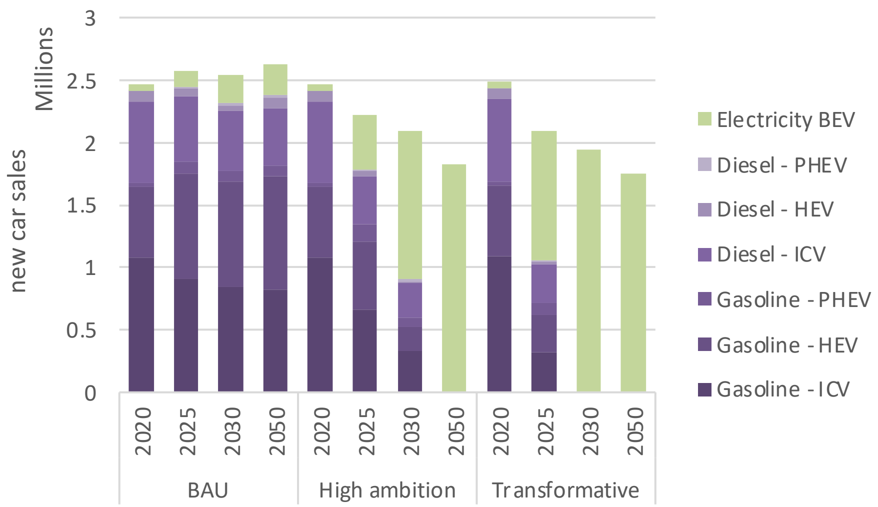

Figure 6. New car sales by primary fuel and propulsion technology.

A SMALLER AND CLEANER VEHICLE FLEET

In a low energy demand world, the car fleet will plateau in the 2020s and gradually, albeit slowly, reduce in size from the current 31 million to about 23 to 25 million in 2050, mainly due to a decrease in driving licence uptake, limits on multi-car ownership and a transition to 'car usership' (car clubs etc). This is substantially lower than the BAU case, which could see up to 43 million cars on the road by 2050 (Frost et al., 2021).

Private, fleet and commercial buyers increasingly prefer BEV over conventional ICV, fuelled by a co-evolving BEV market with increasing availability and performance of zero emission vehicles, faster charging times, investment in home, destination and fast recharging infrastructure, and supporting low carbon pricing policy for zero emission vehicles. Gasoline and diesel ICE (and HEV) vehicles are increasingly 'priced out' of the market as cities start banning conventional vehicles from urban areas. EVs will be widely available in all vehicle segments and by all major brands by 2030. Consumers increasingly accept EVs as the preferred choice over conventional ICV. Large cars such as SUVs will be banned from sale by the mid 2020s. Nevertheless, ICV and HEV continue to be the focus in the short term before BEV and PHEV reach a 50 % market share in the mid to late 2020s, driven by the company/fleet and early adopter markets (Figure 6). Take-up by the mass market and so-called 'user-choosers' (Brand et al., 2017) from the late 2020s mean that BEV take over as the dominant choice of vehicle in this decade, well before the phase out dates of 2030 (ICVs) and 2035 (PHEVs) announced by the UK government (DfT, 2021). Total new car sales decrease over time (Figure 6).

Discussion and conclusions

This paper set out to explore the contribution energy demand reduction in the transport sector could make to climate mitigation efforts. We used a bottom-up modelling framework that comprehensively estimated the potential for mobility-related energy demand reduction at a country level. 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).

We found that reductions in mobility energy demand of 61 % by 2050 compared with baseline levels are possible without compromising on citizens' needs to access jobs and services and wider quality of life. This translates to total lifecycle carbon emissions reductions of up to 72 % by 2050 compared to 2020 levels. About half of the reduction comes from mode shifting and avoiding travel and moving goods, with the other half from vehicle energy efficiency and electrification as well as downsizing of the vehicle fleets. These findings show that energy demand reduction in the transport sector can make it easier to meet sectoral carbon budgets and avoid more drastic car use restrictions further down the line. This trade-off weas supported by members of the recent Climate Assemblies in the UK, where members chose to have the types of cars they could drive restricted to secure only a modest limit on future car use for everyone (Anable, 2020).

The importance of mobility energy demand for the global energy system is clear. The higher the energy demand for mobility, the larger the size of the transport energy system and the slower the transition to carbon-free energy production. Our findings imply that meeting carbon budgets in 2030 and net-zero by 2050 without substantial reductions in energy demand for mobility is difficult, more expensive and probably undesirable. Without reducing energy demand for mobility GHG emission reductions in the sector would need to be delivered through total decarbonisation of a much larger energy supply system and larger vehicle fleets. Given the evidence presented in this paper, it is imperative that the UK Government outline a more detailed strategy and, crucially, supporting policies to enable transport energy demand reduction to fulfil its necessary role in achieving rapid emissions reductions. It may also be too risky to leave the challenge to decarbonise the difficult to decarbonise sectors such as long distance freight and aviation to technological solutions that are not proven at scale or still in development, such as power to liquid (e-fuels) and sustainable aviation fuels.

The limited government focus on energy demand has mostly been on improving technology efficiency with little attention to the other mechanisms that involve reducing the need for mobility. Reducing energy demand to the extent, and at the speed, that is needed requires both an acceleration in energy efficiency improvement and shifts to travel patterns to avoid the consumption of energy services. None of our low energy demand scenarios compromises on our quality of life. Instead, they seek to enhance it with numerous co-benefits associated with active living, clean air, safe communities, rebalancing work and driving down inequality. All this is possible while more than halving the UK's transport energy demand.

The big note of caution is that we seem some way off imagining and delivering the kinds of futures we arrived at. And the door to those futures is not open for ever. If we electrify rapidly and address our demand for energy slowly then lower energy futures will be boxed off as people become locked in to low cost e-mobility. So, the question is whether we are focussed on generating healthier, fairer and fulfilling mobility futures or whether what we are really interested in generating in our mobility futures is more electricity and a bigger, more vulnerable and more expensive set of turbines, wires and plugs to go with it?

References

Aldred, R., & Goodman, A. (2020). Low Traffic Neighbourhoods, Car Use, and Active Travel: Evidence from the People and Places Survey of Outer London Active Travel Interventions. *Findings*, September. doi:https://doi.org/10.32866/001c.17128

Anable, J. (2020) 'You can't always get what you want: a reflection on Climate Assembly UK's deliberations on decarbonising passenger transport, accessed at https://www.creds.ac.uk/you-cant-always-get-what-you-want-a-reflection-on-climate-assembly-uks-deliberations-on-decarbonising-passenger-transport/'. Oxford: Centre for Research Into Energy Demand Solutions (CREDS).

Anable, J. (2021) 'Call for evidence: House of Commons Transport Committee inquiry on zero emissions vehicles and road pricing. CREDS Consultation response 021, February, accessed at https://www.creds.ac.uk/wp-content/uploads/ZEV-roadpricing-Feb2021.pdf'. Oxford: Centre for Research into Energy Demand Solutions (CREDS).

Anable, J., Brand, C., Tran, M., & Eyre, N. (2012). Modelling transport energy demand: A socio-technical approach. *Energy Policy*, 41, 125–138. http://www.sciencedirect.com/science/article/B6V2W-50XTT7B-2/2/cd7e2c97fc5eeafd6dd12903f3c50159

Anable, J., & Goodwin, P. (2019). Chapter 4: Transport & Mobility. In N. Eyre, & G. Killip (Eds.), *Shifting the focus: energy demand in a net-zero carbon UK* (pp. 45–58). Oxford: Centre for Research into Energy Demand Solutions.

BEIS (2019) 'Energy consumption in the UK, accessed at https://www.gov.uk/government/statistics/energy-consumption-in-the-uk on 05/09/2019'. London: Department for Business, Energy & Industrial Strategy.

Brand, C., Anable, J., Ketsopoulou, I., & Watson, J. (2020). Road to zero or road to nowhere? Disrupting transport and energy in a zero carbon world. *Energy Policy*, 139, 111334. doi:https://doi.org/10.1016/j.enpol.2020.111334

Brand, C., Anable, J., & Marsden, G. (2021a) 'The role of energy demand reduction in achieving net-zero in the UK: Transport and mobility: Evidence and assumptions, accessed at https://low-energy.creds.ac.uk/mobility/#evidence'. Oxford: Centre for Research into Energy Demand Solutions (CREDS).

Brand, C., Anable, J., & Morton, C. (2019a). Lifestyle, efficiency and limits: modelling transport energy and emissions using a socio-technical approach. *Energy Efficiency*, 12(1), 187–207. doi:10.1007/s12053-018-9678-9.

Brand, C., Anable, J., Philips, I., & Morton, C. (2019b) 'Transport Energy Air pollution Model (TEAM): Methodology Guide, Working Paper UKERC/DM/2019/WP/01, accessed at http://www.ukerc.ac.uk/publications/team-energy-for-mobility.html on 16/07/2019'. 10 May 2019. London: UK Energy Research Centre, p. 120.

Brand, C., Anable, J., & Tran, M. (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. doi:http://dx.doi.org/10.1016/j.tra.2013.01.010

Brand, C., Cluzel, C., & Anable, J. (2017). Modeling the uptake of plug-in vehicles in a heterogeneous car market using a consumer segmentation approach. *Transportation Research Part A: Policy and Practice*, 97, 121-136. doi:http://dx.doi.org/10.1016/j.tra.2017.01.017

Brand, C., Dons, E., Anaya-Boig, E., Avila-Palencia, I., Clark, A., de Nazelle, A., et al. (2021b). The climate change mitigation effects of daily active travel in cities. *Transportation Research Part D: Transport and Environment*, 93, 102764. doi:https://doi.org/10.1016/j.trd.2021.102764.

Brand, C., Götschi, T., Dons, E., Gerike, R., Anaya-Boig, E., Avila-Palencia, I., et al. (2021c). The climate change mitigation impacts of active travel: Evidence from a longitudinal panel study in seven European cities. *Global Environmental Change*, 67, 102224. doi:https://doi.org/10.1016/j.gloenvcha.2021.102224

CCC. (2018). Reducing UK emissions – 2018 Progress Report to Parliament. London: Committee on Climate Change.

CCC (2019) 'Net Zero – The UK's contribution to stopping global warming, last accessed at https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/ on 20/05/2019'. London: Committee on Climate Change.

Ceccato, R., & Diana, M. (2021). Substitution and complementarity patterns between traditional transport means and car sharing: a person and trip level analysis. *Transportation*, 48(4), 1523–1540. doi:10.1007/s11116-018-9901-8.

Cherrett, T., Allen, J., McLeod, F., Maynard, S., Hickford, A., & Browne, M. (2012). Understanding urban freight activity – key issues for freight planning. *Journal of Transport Geography*, 24, 2232. doi:http://dx.doi.org/10.1016/j.jtrangeo.2012.05.008.

Cohen, S. A., Higham, J. E. S., & Reis, A. C. (2013). Sociological barriers to developing sustainable discretionary air travel behaviour (Article). *Journal of Sustainable Tourism*, 21(7), 982-998. doi:10.1080/09669582.2013.809092.

DfT (2013) 'Road Transport Forecasts 2013, Results from the Department for Transport's National Transport Model'.

London: Department for Transport (DfT), The Stationary Office.

DfT (2016) 'National Travel Survey, 2002-2014: Special Licence Access. [data collection]. 4th Edition. SN: 7553, UK Data Service, http://doi.org/10.5255/UKDA-SN-7553-4'. London: Department for Transport.

DfT (2021) 'Decarbonising Transport: A Better, Greener Britain, accessed at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1009448/decarbonising-transport-a-better-greener-britain.pdf'. London: Department for Transport.

Dunkerley, F., Rohr, C., & Daly, A. (2014). Road traffic demand elasticities: A rapid evidence assessment. Last accessed at https://www.rand.org/pubs/research_reports/RR888.html on 05/01/2018. Cambridge: RAND Europe, Crown Copyright.

EEA (2011) 'Laying the foundations for greener transport - TERM 2011: transport indicators tracking progress towards environmental targets in Europe'. Copenhagen: European Environment Agency.

EEA (2018) 'Electric vehicles and the energy sector - impacts on Europe's future emissions, accessed at file:///Users/christianbrand/Downloads/Electric%20vehicles%20%20and%20the%20energy%20sector.pdf'. Copenhagen: European Environment Agency.

EEA (2020) 'Transport: increasing oil consumption and greenhouse gas emissions hamper EU progress towards environment and climate objectives, accessed at https://www.eea.europa.eu/publications/transport-increasing-oil-consumption-and '. Copenhagen: European Environment Agency.

Frost, S., Massey-Chase, B., & Murphy, L. (2021) 'All aboard: A plan for fairly decarbonising how people travel, accessed at https://www.ippr.org/research/publications/all-aboard'. London: Institute for Public Policy Research.

Fulton, L. M. (2018). Three Revolutions in Urban Passenger Travel. *Joule*, 2(4), 575–578. doi:10.1016/j.joule.2018.03.005.

Gash, V., Mertens, A., & Gordo, L. R. (2012). THE INFLUENCE OF CHANGING HOURS OF WORK ON WOMEN'S LIFE SATISFACTION* (https://doi.org/10.1111/j.1467-9957.2011.02255.x). *The Manchester School*, 80(1), 51-74. doi:https://doi.org/10.1111/j.1467-9957.2011.02255.x

Gota, S., Huizenga, C., Peet, K., Medimorec, N., & Bakker, S. (2019). Decarbonising transport to achieve Paris Agreement targets. *Energy Efficiency*, 12(2), 363-386. doi:10.1007/s12053-018-9671-3

Große, J., Olafsson, A. S., Carstensen, T. A., & Fertner, C. (2018). Exploring the role of daily "modality styles" and urban structure in holidays and longer weekend trips: Travel behaviour of urban and peri-urban residents in Greater Copenhagen. *Journal of Transport Geography*, 69, 138–149. doi:https://doi.org/10.1016/j.jtrangeo.2018.04.008

Haraldsson, G. D., & Kellam, J. (2021) 'Going Public: Iceland's Journey to a Shorter Working Week, accessed at https://autonomy.work/portfolio/icelandsww/'. Alda and Autonomy.

IEA (2021a) 'Global EV Outlook 2021, accessed at https://www.iea.org/reports/global-ev-outlook-2021'. Paris: International Energy Agency.

IEA (2021b) 'Net Zero by 2050, accessed at https://www.iea.org/reports/net-zero-by-2050'. Paris: International Energy Agency.

IEA (2021c) 'Transport sector CO_2 emissions by mode in the Sustainable Development Scenario, 2000-2030, https://www.iea.org/data-and-statistics/charts/transport-sector-co2-emissions-by-mode-in-the-sustainable-development-scenario-2000-2030'. Paris: IEA.

Keith, D. R., Houston, S., & Naumov, S. (2019). Vehicle fleet turnover and the future of fuel economy. *Environmental Research Letters*, 14(2), 021001. doi:10.1088/1748-9326/aaf4d2.

Lam, A., & Mercure, J.-F. (2021). Which policy mixes are best for decarbonising passenger cars? Simulating interactions among taxes, subsidies and regulations for the United Kingdom, the United States, Japan, China, and India. *Energy Research & Social Science*, 75, 101951. doi:https://doi.org/10.1016/j.erss.2021.101951.

Marsden, G., Anable, J., Faulconbridge, J., Murray, L., Roby, H., Docherty, I., et al. (2016) 'Fleximobility: Unlocking Low Carbon Travel, accessed at http://www.disruption-project.net/wp-content/uploads/2016/05/FlexiMobilityFinal.pdf'. Leeds: ITS Leeds.

Marsden, G., Dales, J., Jones, P., Seagriff, E., & Spurling, N. (2018). All Change? The future of travel demand and the implications for policy and planning, First Report of the Commission on Travel Demand, accessed at http://www.demand.ac.uk/wp-content/uploads/2018/04/FutureTravel_report_final.pdf on 08/05/2019. Leeds: Commission on Travel Demand.

Mueller, N., Rojas-Rueda, D., Khreis, H., Cirach, M., Andrés, D., Ballester, J., et al. (2020). Changing the urban design of cities for health: The superblock model. *Environment International*, 134, 105132. doi:https://doi.org/10.1016/j.envint.2019.105132

OECD/ITF (2021a) 'ITF Transport Outlook 2021, accessed at https://www.itf-oecd.org/itf-transport-outlook-2021'. Paris: International Transport Forum, OECD Publishing.

OECD/ITF (2021b) 'Reversing Car Dependency: Summary and Conclusions, ITF Roundtable Reports, No. 181, accessed at https://www.itf-oecd.org/sites/default/files/docs/reversing-car-dependency.pdf'. Paris: International Transport Forum, OECD Publishing.

Philips, I., Anable, J., & Chatterton, T. (2022). E-bikes and their capability to reduce car CO_2 emissions. *Transport Policy*, 116, 11–23. doi:https://doi.org/10.1016/j.tranpol.2021.11.019

Plötz, P., Moll, C., Bieker, G., Mock, P., & Li, Y. (2020) 'Real-world usage of plug-in hybrid electric vehicles: Fuel consumption, electric driving, and CO_2 emissions, accessed at https://theicct.org/publications/phev-real-world-usage-sept2020'. Berlin: International Council on Clean Transportation.

Pye, S., Li, F. G. N., Price, J., & Fais, B. (2017). Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era (Article). *Nature Energy*, 2, 17024. doi:10.1038/nenergy.2017.24

https://www.nature.com/articles/nenergy201724#supplementary-information.

RAC (2021) 'Dependency on the car is increasing, accessed at https://www.rac.co.uk/drive/features/rising-car-dependency-2019/'. London: Royal Autombile Club (RAC).

Ricardo (2019) 'Zero Emission HGV Infrastructure Requirements, Report for the Climate Change Committee, accessed at https://www.theccc.org.uk/wp-content/uploads/2019/05/CCC-Zero-Emission-HGV-Infrastructure-Requirements-Ricardo-Energy-Environment.pdf'. Harwell, uk: Ricardo Energy & Environment.

Schipper, L., & Marie-Liliu, M. (1999) 'Flexing the link between transport greenhouse gas emissions: a path for the World Bank'. Paris: International Energy Agency.

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., et al. (2014). Transport. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, et al. (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

SMMT. (2018). New Car CO_2 Report 2018: The 17th report. London: The Society of Motor Manufacturers and Traders (SMMT).

SMMT (2020) 'SMMT New Car Registrations, September 2020 data, accessed at https://www.smmt.co.uk/2020/10/new-car-registrations-drop-4-4-in-weakest-ever-new-plate-september/ on 5/10/2020'. London: Society of Motor Manufacturers and Traders.

UK Government (2021) 'UN Climate Change Conference UK 2021 - Presidency Programme, https://ukcop26.org/the-conference/presidency-programme/'. London: UK Government.

Vogel, J., Steinberger, J. K., O'Neill, D. W., Lamb, W. F., & Krishnakumar, J. (2021). Socio-economic conditions for satisfying human needs at low energy use: An international analysis of social provisioning. *Global Environmental Change*, 69, 102287. doi:https://doi.org/10.1016/j.gloenvcha.2021.102287

Whelan, G. (2007). Modelling car ownership in Great Britain. *Transportation Research Part A: Policy and Practice*, 41(3), 205-219. http://www.sciencedirect.com/science/article/B6VG7-4MFKD2G-1/2/2d6fdd25e80e598454493a7c21821431.

William, F. L., Thomas, W., Julia, P., Robbie, A., Monica, C., Jos, G. J. O., et al. (2021). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental Research Letters*. http://iopscience.iop.org/article/10.1088/1748-9326/abee4e

Wilson, C., Pettifor, H., Cassar, E., Kerr, L., & Wilson, M. (2018). The potential contribution of disruptive low-carbon innovations to 1.5 °C climate mitigation. *Energy Efficiency*. doi:10.1007/s12053-018-9679-8.