Title: Road to Zero or Road to Nowhere? Disrupting transport and energy in a zero carbon world

Authors: Christian Brand[a,$], DPhil, Jillian Anable[b], PhD, Ioanna Ketsopoulou[c], Jim Watson[c], PhD

[a] University of Oxford and UK Energy Research Centre, South Parks Road, Oxford, OX1 3QY, United Kingdom

[b] Institute for Transport Studies, University of Leeds and UK Energy Research Centre, 34-40 University Road, Leeds, LS2 9JT, United Kingdom

[c] University College London and UK Energy Research Centre, Central House, 14 Upper Woburn Place, London, WC1H 0NN, United Kingdom

[($)] **Corresponding Author**: Dr Christian Brand, University of Oxford and UK Energy Research Centre, South Parks Road, Oxford, OX1 3QY, United Kingdom. Tel: +44(0)1865 285527; Email: christian.brand@ouce.ox.ac.uk. ORCID ID 0000-0002-1535-5328

Abstract

The phasing out of conventional fossil fuel road vehicles is one of a number of potentially disruptive transport and energy policies. The implied technical substitution alone may be too slow to contribute meaningfully to meeting 'net zero' carbon reduction targets. This paper uses established modelling techniques and prospective scenario analyses in a UK case study to investigate what the impacts might be if we were more ambitious, how much disruption is needed to meet climate goals, the role of lifestyle and social change, and the potential implications for key actors in transport energy systems. Existing policies may neither hit carbon reduction targets nor make the early gains needed for a Paris-compliant trajectory. Deeper and earlier reductions in carbon and air quality emissions can be achieved by more ambitious but largely non-disruptive change of a 2030 phase out that includes (plug-in) hybrids. The earlier phase outs combined with lower demand for mobility and car ownership would make significant contributions to an emissions pathway that is both Paris compliant and meets urban air quality goals. Some disruption for technology providers, business and government can be expected in the more ambitious cases. The paper concludes by discussing key policy implications and recommendations.

Keywords: Decarbonising transport; Cars; Vans; Disruption; Lifestyle change; Net zero

Conflict of Interest: The authors declare that they have no conflict of interest.

1. Introduction

1.1 Background and rationale

The transport sector has a significant dependence on oil, with a share of 95% of all global transport energy use in 2015, and this has not changed since the 1970s (IEA, 2018). In the UK, energy use from transport has increased 16.1% since 1990, against an economy-wide decrease of 4.1% and net carbon emissions are unchanged (BEIS, 2018; CCC, 2018c). Transport is also the largest carbon-emitting sector of the UK economy with 28% of greenhouse gas emissions in 2017 (BEIS, 2018; CCC, 2018c). As emissions in other sectors have reduced, transport has grown as a share of overall emissions with no net reduction since 1990 *vis a vis* a 43% reduction for all sectors combined (BEIS, 2018; CCC, 2018c). A lack of progress with heavy goods vehicles and aviation persists, but the unexpected change is the increase in new car 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) (UK Energy Research Centre, 2019). Electric vehicles only accounted for 2.5% of sales in 2018 (DfT, 2019), with seven out of ten sold being plug-in hybrid electric vehicles (PHEVs), which have shown to perform little better in terms of carbon emissions than the most efficient conventional internal combustion engine (ICE) vehicles in real world conditions (Plötz et al., 2018a, b).

Despite well-established pockets of electrification (light and heavy rail) and slowly evolving ones (light duty vehicles and motorised two-wheelers), scenario exercises by fuel companies, international energy agencies, environmental NGOs and utility companies all come to uncannily similar conclusions about the transport sector – a lot of fossil fuel will still be burnt globally within the sector in 2050 and beyond (AEA Technology, 2009; CCC, 2015; IEA, 2011, 2015; Köhler et al., 2009; OLEV, 2013; Sims et al., 2014). Widespread electrification is proving to be a very slow process of incremental change and is likely to be too slow to contribute meaningfully to meeting ambitious climate change mitigation targets. Sprei (2018) argued that the largest disruptive potential lies in the combination of three major innovations of widespread electrification, shared mobility and automation. However, the author acknowledges that *"technology and innovations alone will not be sufficient to create a new sustainable transportation system, regulations will also be necessary"*.

To accelerate the transition to a low carbon transport system, the phasing out of the sale of new conventional gasoline and diesel vehicles by a given date is one of a number of potentially 'disruptive' policies that have been announced over the past five years. Several countries and cities have committed to phasing out conventional vehicles between 2025 and 2040 (WorldAtlas, 2018), with manufacturers also announcing targets (Reiter and Parkin, 2019). A long awaited report by the UK Department for Transport (the 'Road to Zero' strategy, or R2Z), expected to address decarbonisation of the transport sector as a whole, turned out to focus on roads only, with the major emphasis on passenger cars (DfT, 2018a). This included an ambition for ultra-low emission vehicle (ULEV) sales of 50-70% by 2030, and 40% for vans[1], ahead of ending the sale of diesel and gasoline ICE cars and vans by 2040. Criticism was immediate and widespread. Firstly, there remains ambiguity over the

[1] Vans=light commercial vehicles, or LCV

definition of an ULEV, leaving the door open for hybrid electric vehicle (HEV) sales after 2040.[2] Secondly, the 2040 target is weak by international standards, with many calling for this to be introduced a decade earlier (CCC, 2018a; House of Commons, 2018). Thirdly, the policies identified to achieve this are deemed by many to be inadequate. These include improvements to charging infrastructure, maintenance of grants for some ULEV purchases and potential reforms to vehicle tax. The ambition set for vehicle efficiency and fuel decarbonisation falls far short of the scientific evidence on what is required to meet carbon targets. With 60% of UK surface transport's carbon emitted by the car fleet, the sector is pivotal to any post-Paris programme of action. Notwithstanding the most optimistic predictions of carbon intensity based on the new test cycle figures, and the recently agreed cuts in new car and van CO_2 by 2030 (-37.5% and -31% over 2021 levels for cars and vans respectively)[3], the mix of cars sold for the next decade or two will lock in fossil fuels for some time to come (Morgan, 2019).

Overall, there is lack of robust analysis that examines the various targets and phase outs in terms of the key trade-offs in improving carbon emissions, air quality, and public health at various scales. There are also important issues around public acceptability, including how people buy cars, how cars need to be sold, accessed and utilised in order to accelerate turnover in the fleet. As technical substitution alone may be too slow to contribute meaningfully to meeting ambitious targets of reducing carbon emissions (CCC, 2018a; House of Commons, 2018) and local air pollution (Brand et al., 2019a; Palmer and Schwanen, 2019; Quarmby et al., 2019; Williams et al., 2018), the roles of social and lifestyle change in 'avoiding' travel and 'shifting' travel to the most sustainable modes of transport have increased in prominence in the UK (CCC, 2019b; Hopkinson and Sloman, 2019b; Pye et al., 2017; Vaughan, 2019) and globally (Creutzig et al., 2018; IPCC, 2018: Chapter 2). Indeed, in its rather critical response to the R2Z strategy, the CCC pointed to the dangers of relying on technical solutions, suggesting that policies influencing the demand for travel should have a more significant role. They recommended that the Department for Transport should "set out a vision for future travel demand" (CCC, 2018b) and this paper contributes to that vision. Given the required actions may disrupt the transport-energy system, these issues need further investigation through the lens of 'disruption'.

1.2 Aims and objectives

This paper aims to explore the implications of the scale and speed of change via technical substitution and contrasts this with wider social and lifestyle change through the lens of 'disruption'. By doing so it explores whether 'disruption' is needed to reconfigure the transport and energy system or whether incremental, non-disruptive change is sufficient over the next 30 years. The main objectives are:

- To represent and explore disruptive change in transport energy systems;

[2] In the UK Ultra Low Emission Vehicle (ULEV) is the term used to describe any vehicle that: uses low carbon technologies; emits less than 75g of CO_2/km from the tailpipe; and is capable of operating in zero tailpipe emission mode for a range of at least 10 miles (16.1km).

[3] The European Council agreed in late 2018 that from 2030 onwards new cars will be allowed to emit on average 37.5% less CO_2 and new vans will emit on average 31% less CO_2 compared to 2021 levels. Between 2025 and 2029, both cars and vans will be required to emit 15% less CO_2.

- To explore scenarios of disruptive and more incremental change in decarbonising car and van based transport in the UK;
- To assess how disruptive the scenarios may be for key stakeholders of the socio-technical system (who is affected, reach, significance).

By doing so the paper shows what the impacts might be if the Government were more ambitious; how much disruption could be needed to meet climate goals; the role of lifestyle and social change; and the potential implications of disruptive change for key actors in transport energy systems.

2. Methodology and Data

2.1 Analytical framework and scenario mapping

We have used a socio-technical approach to organise policy options and lifestyle change and map their effects on the transport-energy system. The starting point was Unruh's 'Techno Institutional Complex' framework, which has been used to explain the failed diffusion of 'carbon free technologies' (Unruh, 2000, 2002). According to Unruh techno-institutional 'lock-in' is a persistent state that creates systemic market and policy barriers to technological alternatives and occurs through combined interactions among technological systems and governing institutions (Unruh, 2000, 2002). Unruh distinguishes between transition stages as being either end-of-pipe (incremental), continuous (non-disruptive) or discontinuous (disruptive or radical). The original framework (Unruh and Carrillo-Hermosilla, 2006) had two axes of organisation: *degree of disruption* (continuity → disruption) and *degree of lock-in* (developing → industrialised). In line with the literature on socio-technical transitions (e.g. Smith et al., 2005; Yuan et al., 2012), we adapted the latter to *degree* or *level of coordination* so that the adapted framework maps policy scenarios by their *degree of disruption* (continuity → disruption) and the *level of coordination* (emergent transformation → purposive transition). As we will see later (Figure 8), the framework was considered as a tool for organizing policy analysis within the context of large transport-energy based-systems. The framework is further discussed in the editorial article of this Special Issue.

The levels of disruption and coordination may vary according to the actors involved or impacted on. For instance, high and wide ranging EV subsidies (as in Norway) may mean continuity for some actors (e.g. non-car owners, but also car owners) but potential disruption for others (e.g. vehicle manufacturers and their supply chains). Similarly, more sustainable travel patterns may mean reduced car ownership and use, which may be disruptive for vehicle manufacturers and the finance ministry (i.e. the Treasury in the UK). Our analysis therefore distinguishes between four categories of actors:

- Technology providers, industry and business (e.g. car manufacturers, leasing companies);
- Consumers (largely owners and users of cars or vans);
- Organizations and institutions in policy and planning (central government, local government);
- Wider civil society (not everybody owns or uses a car or van).

2.2 Modelling ‘disruption’ and ‘continuity’ in the transport-energy system

Disruption 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). TEAM-UK is a disaggregated, bottom-up modelling framework of the UK transport-energy-environment system, built around a set of exogenous scenarios of socio-economic, socio-technical and political developments. It integrates a transport demand simulation model, household car ownership model, consumer segmented vehicle choice model, vehicle fleet evolution model and vehicle and fuel life cycle emissions model in a single scenario modelling framework. The model projects 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: the time horizon for this study is 2012 to 2050). 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., 2019a; Brand et al., 2017) and policy (Brand et al., 2013) modelling studies. TEAM-UK represents an enhanced version of the UK Transport Carbon Model (Brand et al., 2012) – the main improvements include a wider range of outcome measures (air and noise pollution, land use change) and a more detailed passenger transport demand model. A detailed description is beyond the scope of this paper. The modelling methodology and key methods have been published most recently in Brand et al (2019b).

Briefly, 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 seven main trip purposes (commuting, business, long distance leisure, local leisure, school/education, shopping, 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 economic activity (GDP/capita) and population, with reference demand elasticities taken from a RAND Europe study (Dunkerley et al., 2014).

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[4] 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). New vehicle choice is modelled using a hybrid discrete choice and consumer segmentation model, as described in Brand et al. (Brand et al., 2019b; 2017). New car sales

[4] 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.).

are a function of endogenously derived household car ownership and car scrappage, with the latter modelled as a function of average life expectancy via a S-shaped (modified Weibull) scrappage probability curve (Zachariadis et al., 2001). Based on existing age distributions, average car age was assumed to stay at 6.3 years, with 6.0 years for vans.[5] Total car ownership is modelled based on established methods (DfT, 2013; Whelan, 2007) taking into account household income, average vehicle costs, household location (urban, rural) and car ownership saturation rates for multiple car ownership. Total van ownership is based on extending historic trends based on expected economic growth – a reasonable assumption since road freight has proven rather difficult to decouple from economic growth.

The energy and emissions model calculates fuel and energy consumption as well as pollutant emissions for eight direct pollutants (carbon dioxide, CO_2, methane, CH_4, carbon monoxide, CO, sulphur dioxide, SO_2, nitrogen oxides, NO_X, non-methane volatile organic compounds, NMVOC and particulates, PM) arising from the operation of vehicles by using the established emissions factor method underlying COPERT (EEA, 2012, 2017). This is most detailed for road vehicles, where emissions are based on average-speed emissions-curves for 'hot' emissions as well as excess emissions from 'cold starts' (ibid.). It allows modelling the combined effects of different fleet compositions, different sets of emission factors, traffic characteristics, cold starts, fuel quality, fuel blending (e.g. diesel/biodiesel blends) and driver behaviour.

Last but not least, TEAM-UK includes a life cycle inventory (LCI) model and an environmental impacts assessment (EIA) model based on a typical environmental life cycle assessment framework (ICO, 2006). The life cycle inventory model calculates energy use and emissions (including primary energy and land use) for the manufacture, maintenance and disposal of vehicles; the construction, maintenance, and disposal of infrastructure; and the supply of energy (fuels). This adds 18 unregulated air pollutants and land use change indicators. The environmental impacts assessment model then provides an assessment of the damage caused by calculating impact indicators (e.g. global warming potential) and lower/upper bounds of external costs (e.g. damage costs to human health, social cost of carbon). Further details on methods and data for the LCI/EIA models are given in Brand et al. (2019b).

2.3 Scenario analysis: UK case study

TEAM-UK was applied in a UK case study to compare policy options and map their effects on the transport-energy system in terms of impacts on fleet evolution, energy use, carbon/air quality emissions and revenue streams under the framing of disruption outlined above.

The starting point was the so-called 'Reference' scenario, which depicted existing policy and plans but *without* the proposed ending of the sale of new conventional fossil fuel cars and vans, and *without* any significant changes to travel patterns.

[5] The UK car fleet age profile implied a 50% scrappage probability was for cars or vans that were about 16 years old.

Storylines around future policy ambition and lifestyle change were developed and then quantified to yield a suite of prospective scenarios. First, six alternative 'ban scenarios'[6] were developed and quantified, each with a different policy ambition in terms of (a) target date and (b) definition of what constitutes an ULEV. We explored two target dates (2040 and 2030) and three ULEV definitions (ICE ban, ICE+HEV ban, ICE+HEV+PHEV ban). Second, a 'lifestyle and social change scenario' was developed building on previous UKERC work for Scotland (Brand et al., 2019a), but obviously framed within the UK context and updated with UK data on trip patterns, vehicle fleets, vehicle tax regimes, and so on. The Lifestyle (LS) scenario was then combined with each of the six 'ban scenarios' to generate a total of 14 policy scenarios. Table 1 summarises the narratives and key assumptions for each scenario, with further details provided in Appendix A. To avoid duplication the narratives for the combined 'ban' and 'lifestyle' scenarios are not shown.

Table 1: Narratives and key assumptions for the alternative scenarios for phasing out fossil fuel cars and vans (top half) and the 'Reference' and 'Lifestyle change' scenarios (bottom half – note the combined 'ban' and 'lifestyle' scenarios are not shown)

	Ban (= end the sale of) non-ULEV cars and vans from	
ULEV def.	**2040**	**2030**
ICE ban	*ICE ban 2040:* Availability of new conventional gasoline and diesel ICE cars and vans is drying up from 2035, with no ICE vehicle sold from 2040 onwards. No change in Reference (REF) assumption for the plug in vehicle grant or other incentives.	*ICE ban 2030:* Availability of new conventional gasoline and diesel ICE cars and vans is drying up from 2025, with no ICE vehicle sold from 2030 onwards. Modestly improved market conditions for EVs (consumer awareness, charging infrastructure, increased range of makes and models) from mid-2020s onwards.
ICE+HEV ban	*ICE+HEV ban 2040:* Availability of ICE and HEV cars and vans is drying up from 2035, with no ICE or HEV vehicle sold from 2040 onwards. Much improved market conditions for EVs incl. 'universal' consumer awareness by 2035, increased certainty of access for fleet operations (up to 80%), higher battery capacities, charging rates and faster off-street charging from the late 2020s onwards.	*ICE+HEV ban 2030:* Availability of ICE and HEV cars and vans is drying up from 2025, with no ICE or HEV vehicle sold from 2030 onwards. Much improved market conditions for EVs incl. 'universal' consumer awareness by 2025, increased and earlier certainty of access for fleet operations, higher battery capacities, charging rates and faster off-street charging from the mid-2020s onwards.
ICE+HEV +PHEV ban	*ICE+HEV+PHEV ban 2040:* Availability of ICE, HEV and PHEV cars and vans is drying up from 2035, with no	*ICE+HEV+PHEV ban 2030:* Availability of ICE, HEV and PHEV cars and vans is drying up from 2025, with no

[6] In this paper we have used the term 'ban' interchangeably with 'end of sale of', largely to cut down the word count and shortening the scenario labels.

	ICE, HEV or PHEV vehicle sold from 2040 onwards. Much improved market conditions for EVs incl. 100% consumer awareness and certainty of access for fleet operations by 2040, higher battery capacities, charging rates and faster off-street charging from the late 2020s onwards.	ICE, HEV or PHEV vehicle sold from 2030 onwards. Much improved market conditions for EVs incl. 100% consumer awareness and certainty of access for fleet operations by 2030, higher battery capacities, charging rates and faster off-street charging from the mid-2020s onwards.
Reference (compariso n scenario)	*REF*: Projection of transport demand, supply, energy use and emissions as if there were no changes to existing transport and energy policy. No ban. Consumers increasingly shy away from diesels post 'Dieselgate' (Brand, 2016). Existing UK plug-in vehicle grant (OLEV, 2018) for cars, vans, taxis and motorcycles (up to £3,500 for cars, depending on how 'plugged-in' the vehicle is) to be 'phased out' gradually in the 2020s. Consumer awareness of EVs increases to ~50% by mid 2020s then levels out. Certainty of access to charging for fleet operations stays at 40%. Private access to overnight charging level at 70%. See Brand et al. (2019b) for detailed assumptions of the Reference case.	
Lifestyle change (+ combinatio ns with ban scenarios)	*LS*: Radical change in travel patterns, mode choice and occupancy levels leading to relatively fast transformations and new demand trajectories. Concerns relating to health, quality of life, energy use and environmental implications drive social change. Shift away from mobility towards accessibility of services and jobs and from speed to quality and resilience of journeys. Triggered by worsening conditions, social norms promote status of more sustainable modes of transport and demote single-occupancy car travel, fossil fuelled vehicles, unnecessarily long distances and speeding. Current car-based systems increasingly replaced by zero emission public transport, active travel, and shared mobility. ICT facilitates rapid behavioural change by making cost and energy use transparent to users, changing everything from destination choice, substitution of shopping and personal business trips by home delivery, car choice and models of 'ownership', driving style and paying for travel, including in the freight sector. Renewed focus on localism. Changes in work patterns and business travel fuelled by renewed emphasis on quality of life but also facilitated by increasingly sophisticated ways of substituting disproportionally impactful long commuting and business trips by digital technology. Increased internet shopping *increases* the use of vans, which somewhat offsets the positive effects of decongestion from fewer cars on the road.	

The assumptions on the electricity generation mix was based on the 2018 Energy and Emissions Projections . Embedded carbon emissions factors were based on Pehl et al. (2017), with specific emissions for nuclear, wind and solar photovoltaics reported in the range 3.5-11.5 gCO_2/kWh. Based on the TEAM life cycle inventory model and including transmission and distribution losses of 7%, the carbon content of supplied electricity is gradually decreasing from about 335 gCO_2/kWh in 2015 to 178 gCO_2/kWh by 2020, 98 gCO_2/kWh by 2035 and 46 gCO_2/kWh by 2050.

3. Results and Discussion: main scenario modelling outputs

3.1 Travel demand

Travel patterns do not change significantly in the ban scenarios, with the modelling suggesting only marginal increases in car travel (<0.5%) as a result of lower overall costs of EV ownership and use. This is as expected as the bans target *improving* the efficiency and carbon content of travel, not travel reduction or mode shift. Notably, solely electrifying cars and vans will not address traffic jams, urban sprawl, transport inequality, sedentary lifestyles, road safety, space for parking and support for local economies (Anable and Goodwin, 2019; Hopkinson and Sloman, 2019a).

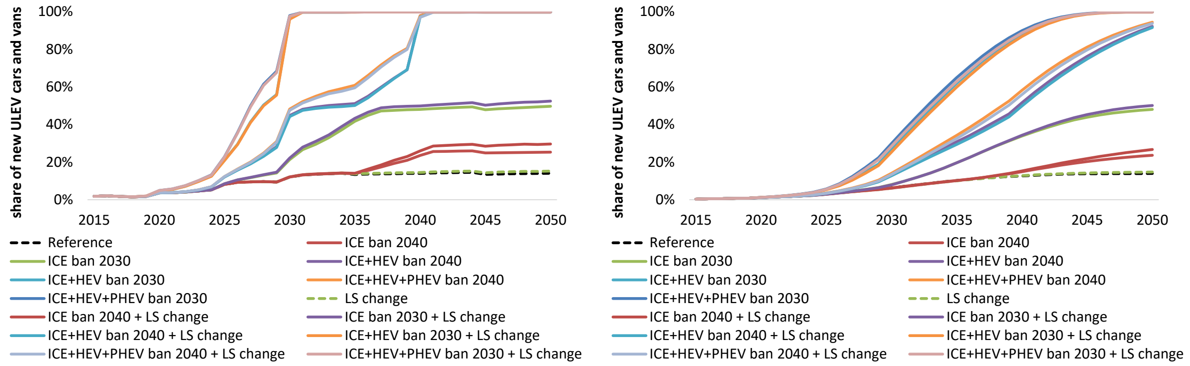
Travel patterns do change considerably in the lifestyle scenarios, which focus on *avoiding* travel and *shifting* travel to more sustainable modes such as public transport and new mobility services. Mode shift is combined with destination shifting as trips are either fully removed from the system through 'virtual travel' or shorter as a result of localisation. As a result, overall passenger travel demand decreases 2% by 2030 and 12% by 2050. The distance travelled by car as a driver or a passenger decreases 20% by 2030 and 51% by 2050, with increases in bus travel (+172% for urban bus, express coach and rural mini bus services combined), motorbike travel (+209%) and cycling and walking for shorter trips towards the latter part of the period. People increasingly use a multitude of modes in the lifestyle scenarios. While in 2015 the car was used for the vast majority of distance travelled as a driver or passenger (79%), this drops to 65% by 2030 and 44% by 2050. This reflects the assumption that cars are increasingly banned or priced out of city/town centres. At the same time, cycling goes from accounting for less than 1% of distance travelled to 4% by 2030 and 8% by 2050, mainly replacing short car trips under 5 miles. This is similar to levels seen today in countries regarded as demonstrating best practice in this area: in 2014 an average Dutch person cycled almost 1,000 km per year, corresponding to around 9% of total distance travelled and a trip mode share of 28% (Statistics Netherlands, 2016). This more active lifestyle means less obesity, pollution and road danger – and greater sociability as people meet their neighbours on their way to work. It also allows parking spaces to be 'liberated' for more housing or gardens.

3.2 Fleet turnover and ULEV uptake

The total UK fleet of cars and vans was 34.0 million in 2016, comprising 30.8 million cars 3.2 million vans. In the ban scenarios, the total fleet is expected to increase to 38.2 million by 2030 and 44.1 million by 2050. In contrast, and driven primarily by lower household and fleet car ownership in the lifestyle scenarios, the total fleet is projected to increase at lower rates to 34.9 million by 2030 and then reduce in size to 31.7 million by 2050. This is on the back of expected growth in the UK population and wider economy. Also, lower demand for mobility and car ownership in the lifestyle change scenarios imply a delayed turnover of the fleet, as fewer ULEVs enter the market each year. Fewer cars combined with shared and more multi-modal mobility will have the benefits of reduced congestion, less parking infrastructure and road expansions, less inequality and improved road safety (Anable and Goodwin, 2019).

In terms of fleet technology evolution, the modelling suggests that existing policies – i.e. the *Reference* case without a strict ban or further policy action – will have a positive, if modest, effect on electrifying the fleet, with ULEV cars and vans (= BEV and PHEV) expected to increase their market share from approx. 2% in 2018 to about 14% by 2030 (Figure 1a, left). Of course, total fleet turnover lags behind new sales by 10-15 years, so any benefits of this transition will only materialise from the mid 2030s onwards (Figure 1b, right).

Figure 1: Scenario comparison of the share of sales (a: left) and total fleet (b: right) of ULEV cars and vans



In contrast, gasoline and diesel ICE cars and vans are gradually phased out of the market in the ban scenarios as the policy signal of the impending ban on conventional vehicles bears fruit. This happens, of course, at different rates and scales depending on the ambition of the ban and underlying policies. Firstly, in the ICE-only bans (that allow conventional HEVs to be sold beyond the ban date), the shift towards ULEVs is modest and driven by the 'fleet' and 'enthusiast' markets (Brand et al., 2017), with shares of new ULEVs up to 26% (*ICE ban 2040*) and 49% (*ICE ban 2030*) once the bans have been introduced. Secondly, in the more ambitious bans that include ICE and HEV vehicles, private, company and fleet buyers increasingly prefer ULEVs over conventional ICE and HEV vehicles, fuelled by a co-evolving EV market with increasing availability and performance of lower carbon vehicles and growing investment in home and fast recharging infrastructure. In the *ICE+HEV ban 2040*, ULEV take-up by the early adopter and mass markets and so-called 'user-choosers' (i.e. the segment of private buyers purchasing a company or fleet vehicle, see Brand et al., 2017) starting in the late 2020s mean that ULEV vehicle sales reach the 50% mark by the early 2030s, with 100% take-up by 2040 as expected by the policy. Moving the ban date forward to 2030 (*ICE+HEV ban 2030*) increases the rate and scale of the transition to plug-in vehicles, with nearly 50% of sales being ULEV by the mid 2020s and 100% take-up by 2030. Thirdly, when also including PHEV in the bans the results do not change much from the ICE+HEV bans, which showed low take-up rates of PHEV in favour of BEVs. The main difference is that ULEV are taken up a few years earlier than in the ICE+HEV scenarios. So overall, we would expect little change in the early 2020s but a profound shift in vehicle buyers' technology preferences and choices in the late 2020s (earlier phase out) or late 2030s (later phase out).

In terms of meeting the objectives of the R2Z strategy (DfT, 2018a), the results suggest that the R2Z 'mission' for all new cars and vans to be 'effectively zero emission' by 2040 – and the R2Z 'ambition' of 50% new 'ULEV' by 2030 – would only be met by including HEVs in the ban.[7]

The continued sale of conventional ICE and HEV gasoline and diesel vehicles – and relatively lower shares of ULEVs in the fleet – implies that there would still be a lot of fossil fuel cars and vans on the road in 2050, particularly in the *ICE ban* scenarios (Figure 1, right). As for diesels, we expect between zero (*ICE+HEV ban 2030, ICE+HEV+PHEV ban 2030*) and 4.0 million (*ICE ban 2040*) vehicles on the road in 2050. While this is significantly lower than the total fleet of 11.4 million diesel cars and vans in the *Reference* case, it suggests that an effective phasing out of fossil fuelled cars and vans by 2050 may only happen with earlier ban target dates and a stricter definition of what constitutes a ULEV (*ICE+HEV 2030, ICE+HEV+PHEV 2030)*. This confirms the results of other work (e.g., CCC, 2018a).

3.3 Progress towards meeting carbon emissions targets and cumulative budgets

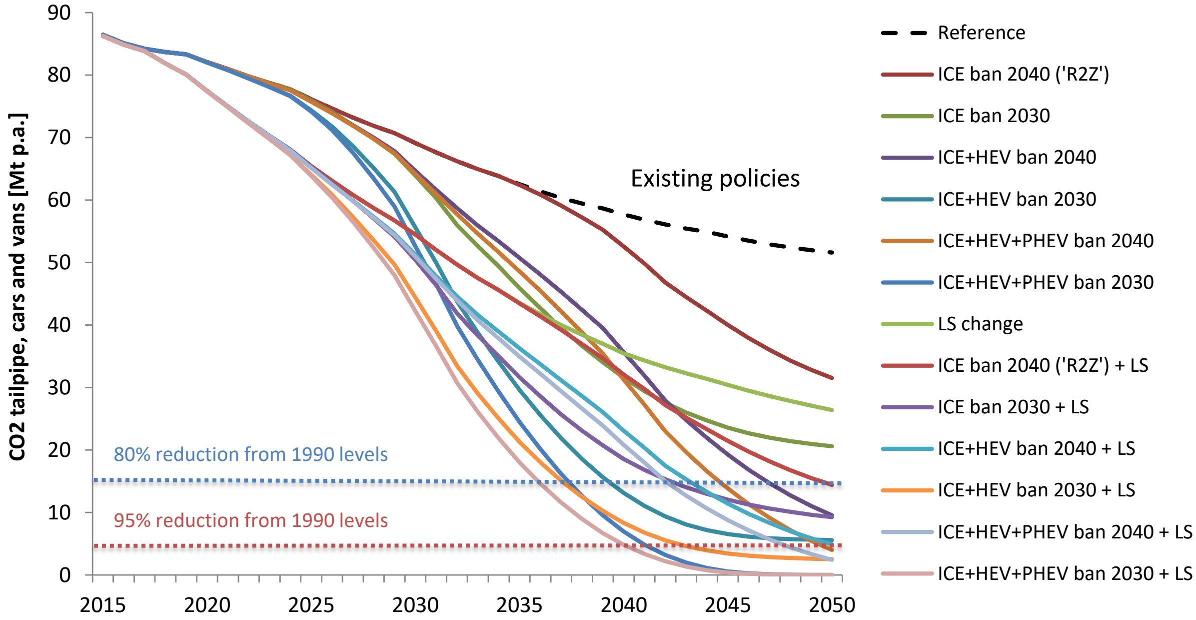
Figure 2 shows direct (tailpipe) CO_2 emissions from UK cars and vans compared to two emissions reduction targets for 2050: an 80% reduction that is in line with the Climate Change Act 2008; and a more stringent 95% target that is closer to the requirement for a net zero economy (BEIS, 2019c).[8] This illustrates a number of points. First, the modelling suggests that existing policies achieve some reduction in direct emissions, mainly due to efficiency improvements and technical substitution described earlier[9]. The 'R2Z' (*ICE ban 2040*) scenario neither hits the targets nor makes the early gains needed, suggesting the strategy may achieve too little, too late. This confirms the results of other research (CCC, 2018a; House of Commons, 2018). Second, progress towards the -80% and -95% targets across the range of bans was mixed – with the latter only met in the earlier and more stringent ban. The largest and earliest savings were in the 2030 bans that phased out HEV and PHEV by 2030 combined with more sustainable travel patterns. While slightly less ambitious, the phasing out of ICE and HEV (but not PHEV) by 2030 resulted in 20% and 82% reductions in tailpipe CO_2 emissions by 2030 and 2050 when compared to the 'R2Z' scenario (*ICE ban 2040*). Third, lifestyle change on its own gave 21% (2030) and 16% (2050) lower tailpipe CO_2 emissions than the R2Z, so *earlier* and higher gains across the assessment period. Finally, the 2040 target scenarios reached similar reductions only in the second half of the assessment period, with lower demand for mobility doing the 'heavy lifting' early on.

[7] The strategy sets an interim ambition for ultra-low emission vehicle sales (ULEVs) of 50-70 per cent by 2030, and 40 per cent for vans, ahead of a ban on diesel and gasoline cars and vans by 2040.

[8] Based on baseline 1990 emissions of 70.3 $MtCO_2$ for cars and 11.5 $MtCO_2$ for vans, i.e. a total of 81.8 $MtCO_2$. Assuming national targets were shared equally across the economy, the transport sector and cars and vans, the legislated -80% and the 'near zero' -95% targets were 16.4 MtCO2 and 4.1 MtCO2 respectively.

[9] This analysis is dependent on the assumption that new car and van CO_2 emissions for all propulsion systems will undergo continuous improvement driven by new car and van CO_2 regulations and that a significant proportion of miles undertaken in PHEVs will use the electric battery (largely for urban driving, i.e. approx. 33% of the total mileage with motorway and rural driving assumed to mostly use the ICE). This compares to 73% of PHEV driving done in electric mode assumed in the R2Z (DfT, 2018) analysis.

Figure 2: Comparison of direct (tailpipe) CO_2 emissions from cars and vans in the UK

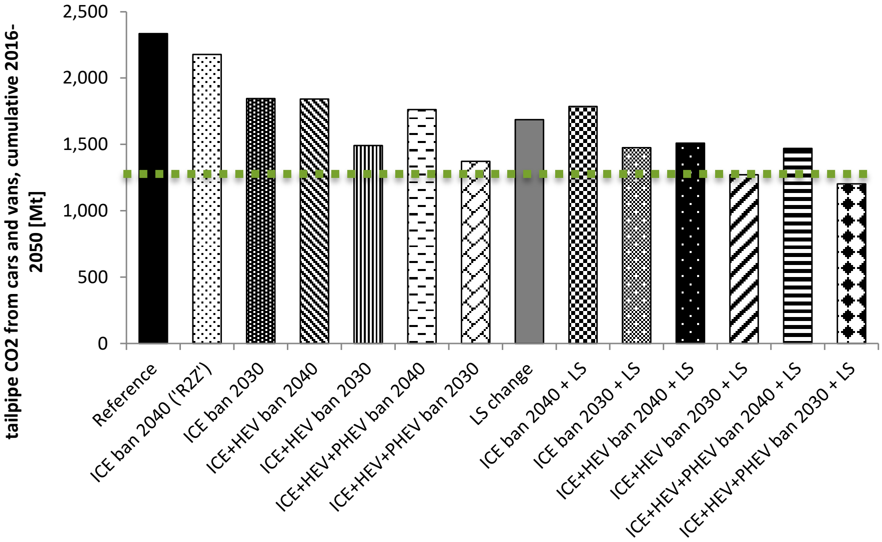


ICE=internal combustion engine; HEV=hybrid electric vehicle; PHEV=plug-in hybrid electric vehicle; R2Z=Road to Zero; LS=lifestyle and social change; Mt=million tons.

Another way of looking at this is through the assessment of cumulative emissions and carbon budgets. Here we first needed to look at remaining global budgets then make assumptions on the remaining UK budget and the role cars and vans might play. The starting point for our analysis was the remaining global budget of 580 $GtCO_2$ (from 01/01/2018) that reflects a 50:50 chance to stay below 1.5°C (IPCC, 2018: Table 2.2). Taking this back to 2016 (where we have global and UK emissions data) implies adding two years of emissions (about 80 $GtCO_2$), yielding a remaining budget of 660 $GtCO_2$ (from 2016). Based on the premise that this global budget is distributed on an equal per capita basis (following approach by Rahmstorf, 2019), this gives a remaining UK budget of 5.85 $GtCO_2$ (from 2016). We then required the potential share of this UK budget that remained for cars and vans. When compared to total 2016 UK CO_2 emissions (excluding international aviation and shipping) of 378.9 $MtCO_2$, cars and vans emitted 88.7 $MtCO_2$ – i.e. a 23% share of the total (DfT, 2018b: Table ENV0202). So, the remaining budget for cars and vans was estimated as 1.369 $GtCO_2$.

Figure 3 compares the different scenario pathways in terms of cumulative emissions over the period from 2016 to 2050. While in the Reference and 'R2Z' cases car and van emissions would use up 40% and 37% of the remaining UK budget on their own, the earlier bans combined with lower demand for mobility and car ownership would make significant contributions to reducing emissions within the remaining UK budget. The most stringent case (*ICE+HEV+PHEV ban 2030 + LS change*) totalled 1.2 $GtCO_2$ over the period from 2016 to 2050 (or 21%), so within a potential 23% share of the remaining budget (1.369 $GtCO_2$). Note the estimate of a remaining budget can be considered an upper limit, as the budgeted emissions do not include international aviation and shipping and the share of emissions do not change over time. Van emissions are expected to increase more than total country emissions due to rising travel demand; and long-distance freight and aviation are difficult to electrify – a cornerstone of the emissions pathways for cars and vans explored here.

Figure 3: Cumulative CO_2 tailpipe emissions from cars and vans, 2016-2050 period

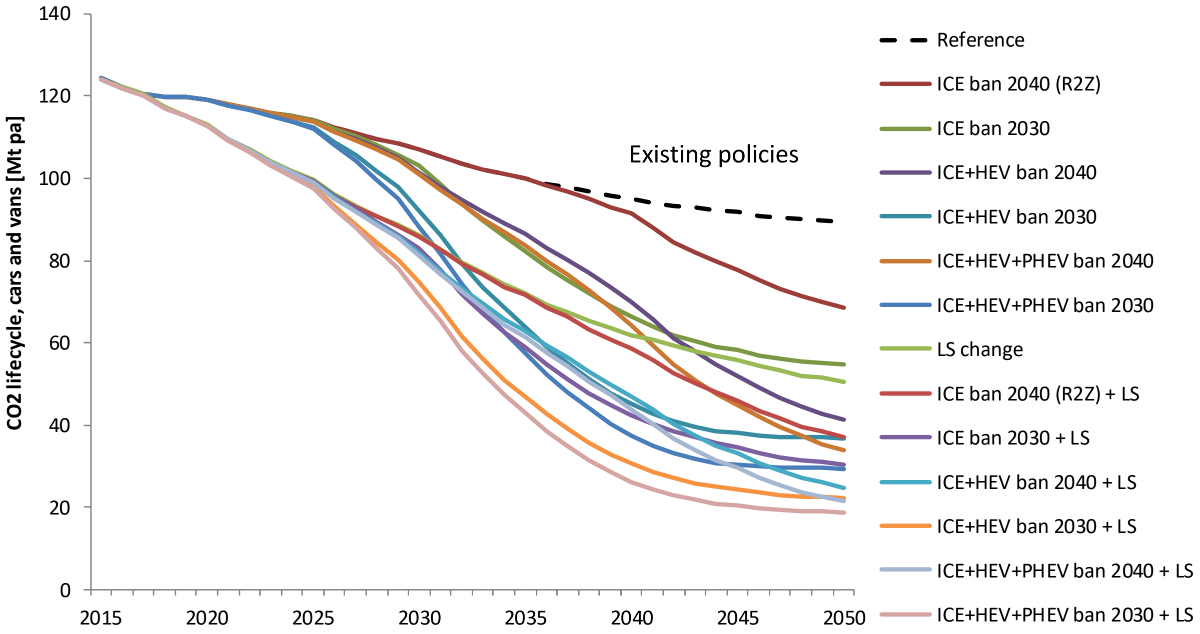


Notes: the green dashed line depicts a potential Paris compliant carbon budget left for cars and vans, based on equal per capita emissions, constant share of total UK emissions for cars and vans, and excluding international aviation and shipping (see main text for details). ICE=internal combustion engine; HEV=hybrid electric vehicle; PHEV=plug-in hybrid electric vehicle; R2Z=Road to Zero; LS=lifestyle and social change; Mt=million tons.

So, the story so far is that the phasing out of fossil fuel vehicles combined with lower demand for mobility can achieve deep, if sometimes insufficient, reductions in tailpipe carbon emissions – but what about adding indirect emissions from the full fuel and vehicle lifecycle? Total life cycle emissions are shown in Figure 4, suggesting that adding upstream and downstream CO_2 emissions from vehicle manufacture, maintenance & disposal and the supply of energy (fossil fuel production, electricity generation) basically shifts the emissions trajectories up by between 19 and 38 $MtCO_2$ p.a. by 2050. This is largely due to *total* upstream and downstream CO_2 emissions (vehicle and fuel LCA data based on Kay et al., 2013; Odeh et al., 2013) remaining roughly constant over time as emissions from the generation and distribution of electricity replace those from fossil fuel production and distribution. While the increase in electricity use in the high electrification scenarios is significant (see also Figure 6 below), the significant decrease in the carbon content[10] coupled with decreases in upstream emissions from fossil fuel production balance each other out. Further analysis showed that the combined upstream carbon emission from electricity generation and fossil fuel production for cars and vans decreased from 15.9 $MtCO_2e$ in 2015 to between 13.0 $MtCO_2e$ (all 2030 ban scenarios) and 13.4 $MtCO_2e$ (*Reference* and *ICE ban 2040*) by 2030. By 2050, this decreased further to between 4.5 $MtCO_2e$ (*ICE+HEV ban 2030*) and 7.3 MtCO2e (*ICE ban 2040*), which is lower than the 10.2 $MtCO_2e$ in the Reference case. So, upstream fossil fuel emissions were partially replaced by the increases in electricity generation emissions. It is worth noting that not all of upstream and downstream emissions are within the UK boundaries or accounts; therefore, a direct comparison with national climate change targets is inappropriate.

[10] As highlighted in Section 2 the carbon content of supplied electricity is assumed to gradually decrease from 335 gCO_2/kWh in 2015 to 178 gCO_2/kWh in 2020, 98 gCO_2/kWh in 2035 and 46 gCO_2/kWh in 2050.

Figure 4: Comparison of life cycle CO_2 emissions from cars and vans in the UK



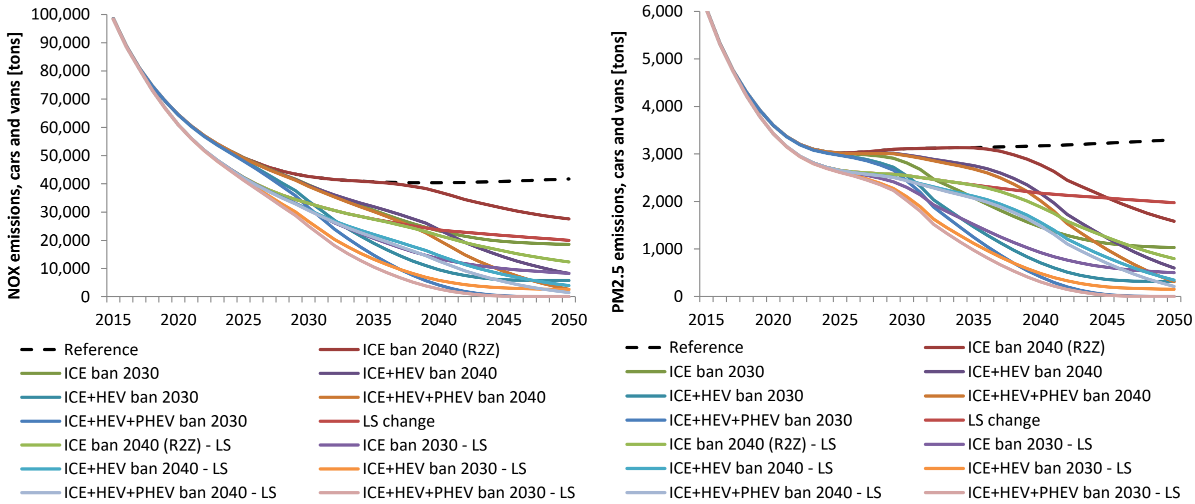
ICE=internal combustion engine; HEV=hybrid electric vehicle; PHEV=plug-in hybrid electric vehicle; R2Z=Road to Zero; LS=lifestyle and social change; Mt=million tons.

3.4 Progress towards improving air quality

The phasing out of conventional fossil fuel cars and vans explored here can accelerate reductions in air quality emissions in the medium to long term, but not the short term. Lower demand for mobility and car ownership in the lifestyle change scenarios fair better as they can achieve earlier and more significant gains from the early 2020 onwards. Figure 5a (NO_X, left) and Figure 5b ($PM_{2.5}$, right) illustrate downward trends for all scenarios in the short term, largely due to lower emission ICE and HEV (and some plug-in) vehicles replacing older more polluting ones. This trend levels off and even increases in the longer run in the ban scenarios due to higher demand for travel and no further improvement to the current EURO6 emissions standards[11]. In contrast, NO_X and $PM_{2.5}$ emissions decrease in the lifestyle change scenarios as fewer vehicles are in use.

[11] While this is a valid "existing policies" assumption it is worth noting that post-EURO 6 standards (and a broader range of emissions types) are currently being developed by the European Commission, so it is likely that we will see further reductions in NO_X and $PM_{2.5}$ in future years.

Figure 5: Scenario comparison of direct NO_X (a: left) and $PM_{2.5}$ (b: right) emissions from cars and vans

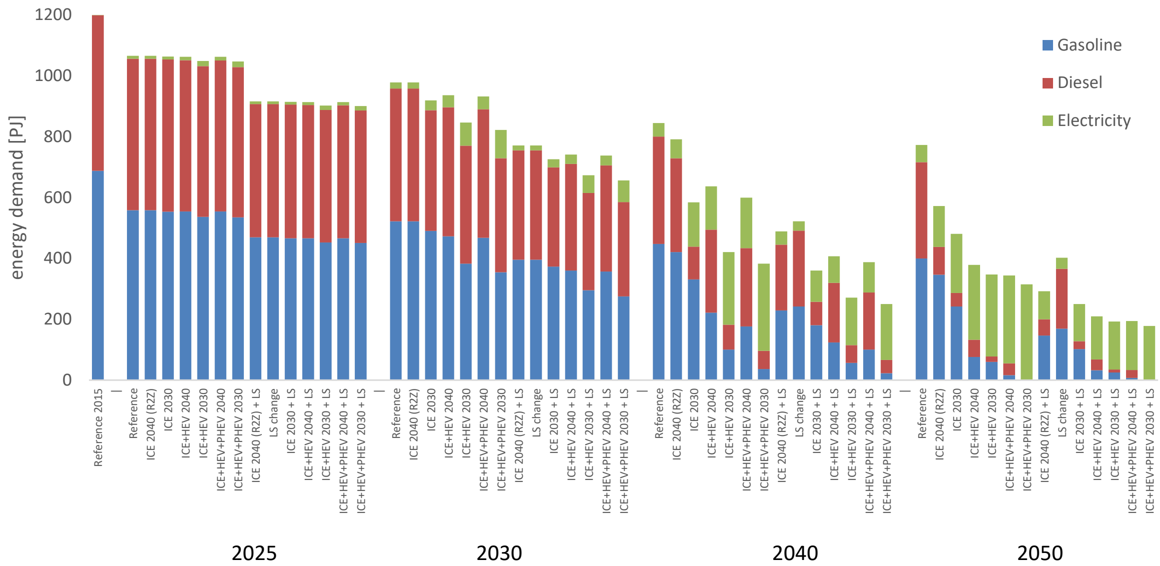


From the mid 2020s onwards tailpipe NO_X and $PM_{2.5}$ emissions decreased *more* in the 2030 and lifestyle scenarios than in the 2040 scenarios (Figure 5). The R2Z case (*ICE ban 2040*) only shows air pollution benefits from the late 2030s onwards. This suggests that in order to reduce the health burden of road traffic pollution faster, the earlier transformation to a cleaner ULEV vehicle fleet coupled with lower demand for mobility is likely to be more effective than existing UK Government strategy (UK Clean Air Strategy, R2Z), which in its own admission expects to breach international air quality standards well into the 2020s (Defra, 2019). In addition, more stringent and broader post-EURO6 standards are needed to bring down emissions further, particularly with regards to ultrafine particles and non-regulated pollutants that act as precursors to particulate matter (Rodríguez et al., 2019).

3.5 Energy demand

In the short term (until about 2025) the phasing out scenarios showed a gradual decrease in overall energy use, which is due to improvements in vehicle energy efficiency outpacing increases in demand for car (+6% between 2015 and 2025) and van (+16%) travel (Figure 6). More modest reductions in energy demand were modelled in the lifestyle cases. Demand for electricity was marginal except for the 2030 bans of hybrids and plug-in hybrids.

Figure 6: Transport energy demand from cars and vans (in PJ) for the main transport fuels



In the medium to longer term the modelling showed modest (2030) to large (2050) decreases in energy consumption due to lower demand for mobility (LS variants) and the uptake of more energy efficient plug-in vehicles (ban scenarios). Energy demand reductions and fuel switching away from fossil fuels was largest in the more stringent and earlier scenarios, with energy demand from cars and vans (in PJ) decreasing by up to 74% (bans) and 85% (bans + lifestyle) by 2050 when compared to 2015. This contrasts to a decrease of 36% by 2050 in the *Reference* scenario. By 2050, fossil fuel demand decreases further by -40% in the *Reference* case, -63% in the R2Z case (*ICE ban 2040*), -89% in *ICE+HEV ban 2040* and -100% in *ICE+HEV+PHEV ban 2030*. Lower demand for mobility alone achieves reductions in fossil fuel energy by -69% by 2050, which is significant.

By comparison, electricity demand for cars and vans grows steeply from a low base of only 0.5 PJ in 2015, particularly in the second half of the period. By 2050, electricity use accounted for the majority of energy use in transport in the scenarios that implied maximum electrification without demand reduction (between 247 PJ and 315 PJ, compared to 57 PJ in the *Reference* case). To put this into context, electricity consumption in the UK was 1,080 PJ (300 TWh)[12] in 2017 (BEIS, 2019a: Table C1), so electrification of a larger 2050 car and van fleet would add about 23%-29% to current demand. Note the figures compare to those by the CCC who expect additional demand for road electricity under a 'Further Ambition' (i.e. high electrification) scenario to be about 290 PJ (80 TWh) by 2050 (CCC, 2019a).

Crucially, lower demand for mobility means that the amount of electricity needed to power cars and vans in the lifestyle scenarios was lower than without lifestyle change (between 142 PJ and 179 PJ by 2050, compared to 36 PJ in the *Lifestyle* case), thus putting less pressure on the grid (particularly low voltage distribution) to be upgraded and saving costs in the process.

[12] 35.2% of consumption was in the residential sector, with the remainder used by businesses (32.4%), industry (30.8%) and transport (1.6%, of which only 0.1% was for road transport).

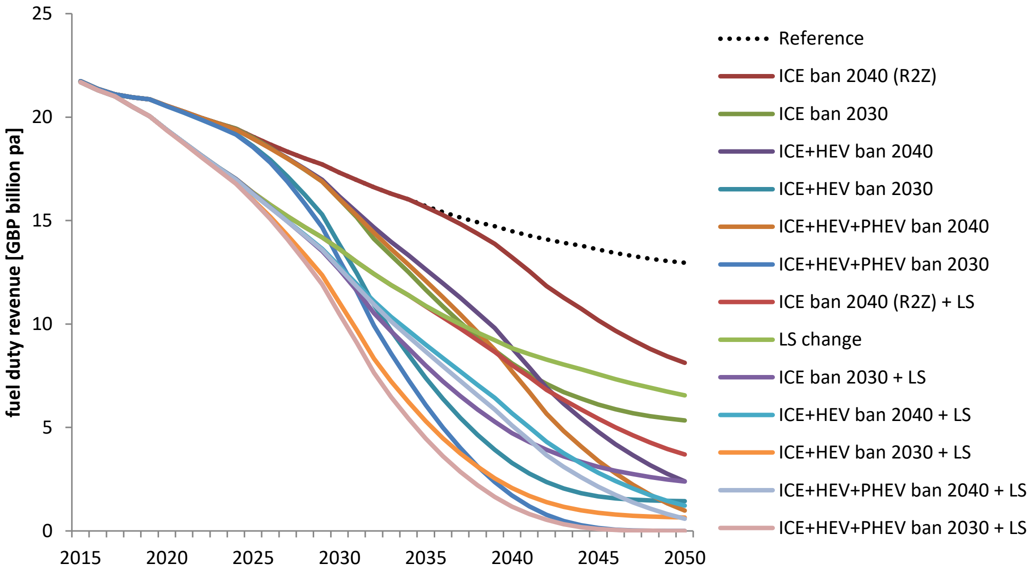
3.6 Road fuel duty

HM Treasury (the UK's finance ministry) currently takes about £21.7 Billion per year from cars and vans, which is almost entirely from the duty on gasoline and diesel of GBP0.58/litre (HM Treasury, 2018). While road tax revenue streams would not change significantly in the short term, they would fall more sharply from the late 2020s onwards reflecting zero duty on electricity. By 2050, this revenue stream would virtually be wiped out in all scenarios that ban fossil fuel vehicles.

To compensate for this loss, a number of policy options have been suggested, including the introduction of a road fuel duty on electricity and dynamic road pricing. As for the former, a duty on road electricity would need to be in the order of 15 to 20 pence per kWh to compensate for revenue losses, depending on the scenario. Such a road fuel duty would more than double the price of electricity (from 14 p/kWh to 34 p/kWh) and, therefore, affect operating costs. For instance, for private users it would add £530 p.a. to operating an average medium (category B/C) BEV car in 2030 – slightly more (£663 p.a.) for company cars owned by fleet managers as these vehicles are driven further. Adoption is also slowed somewhat in the scenarios where only ICE vehicles are phased out. For instance, in the case of a 2030 ban on ICEs only (*ICE ban 2030*) the additional road fuel duty lowers the share of new ULEVs from 21% to 17% in 2030 and 50% to 44% in 2050. The more ambitious *ICE+HEV* and *ICE+HEV+PHEV* bans see less of a decrease in ULEV uptake, as non-electric alternatives are simply not available for sale after the ban date. It has been suggested, however, that a per-kWh duty may not be a workable solution as there would not be an easy way of separating out electricity used for road vehicles from that used for powering domestic residences and commercial buildings. The option of installing two smart meters in a home would bring challenges of tax avoidance and fraud on top of any administrative burdens. Fuel duties also tend to be regressive. More generally, road fuel duties do a poor job of capturing the costs of congestion, which vary hugely by time and place.

Which brings us to the second option, dynamic road pricing. Road pricing has long been suggested as a more feasible alternative. The UK's Institute for Fiscal Studies (Adam and Stroud, 2019), for instance, recommended a system of road pricing under which the charges for driving would vary according to the time of day and the location. Of course, such a system would need to be implemented in a non-regressive manner and require significant investment in 'smart' technology and acceptance by users and industry – issues that are being explored in House of Commons Transport Committee (UK House of Commons, 2019).

Figure 7: Government revenue from road fuel duty on gasoline and diesel, cars and vans only



4. Implications for the main actors: disruption or continuity?

Legislated bans on the sale of new conventional fossil fuel vehicles will involve high levels of coordination, intention and buy-in by policy makers, business and wider civil society. This perhaps differs from uncoordinated change such as in the case of social and lifestyle change supported – but not entirely driven – by policy and regulation. The nature of lifestyle and social change can be considered as a mix of emergent transformation (e.g. travel behaviour change may emerge from concerns about air pollution 'deaths' and 'climate emergency' in some segments of the population but not in others) and purposive transition (e.g. lifestyle change is encouraged through a coordinated 'push and pull' policy approach). Given the multitude of elements and complexity of interpretation of a lifestyle transition we focus the remainder of discussion in this Section on the phasing out policies.

In terms of the types of change, our results imply that in the 'Road to Zero' (*ICE ban 2040*) pathway the main actors of the road transport and energy system are unlikely to undergo disruptive change. This is due to the relatively slow and limited evolution of the fleet towards 'unconventional' low carbon fuels, continuation of fuel duty revenue streams well into the 2040s and little additional reductions in energy demand and air pollutant emissions.

However, in the earlier (2030) and stricter (in ULEV terms) pathways we can expect *some* disruption for technology providers, industry and business – in particular vehicle manufacturers, global production networks, the maintenance and repair sector as well as the oil & gas industry. There will also be localised impacts (some potentially disruptive) on electricity distribution networks and companies. Figure 8 is an attempt to map this out. There may be significant employment disruptions, e.g. due to internal combustion engine plants closing unless restructuring to EV production is successful and in time, and the policy instruments to foster the shift can be expected to generate backlash.

The stronger policy signal of a 2030 ban that includes hybrids would provide certainty to manufacturers to invest and innovate, backed up by much improved market conditions for EVs that go beyond the R2Z strategy. Measures such as increased consumer awareness through marketing and awareness campaigns and increased and earlier certainty of access for fleet operations could help to manage the potential disruption, while technological developments such as higher battery capacities, charging rates and faster off-street charging might also mitigate this from the mid-2020s onwards.

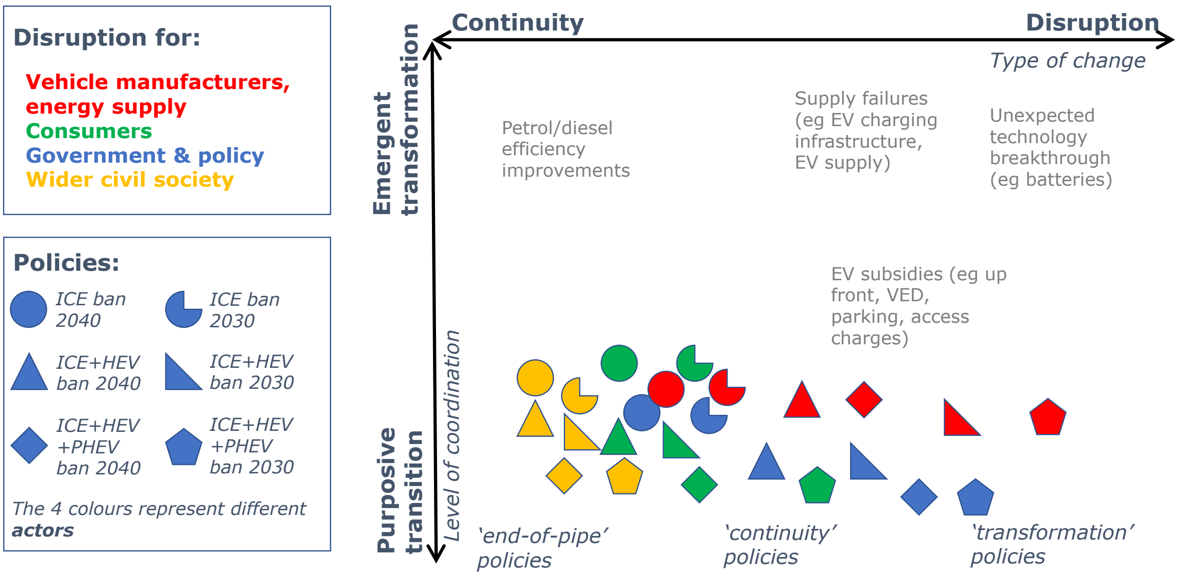
If the UK succeeded in phasing out conventional *and* hybrid EV cars and vans, the UK oil and gas industry would gradually lose an important demand sector at potentially disruptive rates of change in the medium term (beyond 2030). However, some global scenario exercises (e.g. BP, 2019: Rapid Transition scenario) suggest that even a 2030 ban wouldn't affect total oil demand very much because oil is used in many other modes of transport (aviation, shipping, heavy goods vehicles, rail) and sectors of the economy. The potential loss of fuel duty revenues from fossil fuel use has been recognised as a potentially disruptive change (Howard et al., 2017). However, some commentators have argued that the loss of annual income does not matter when compared to the wider economy, as the level of excise from road fuels is similar to the annual changes in expenditure and payments discussed at budget time (BVRLA, 2019). In any case, any loss could be compensated by introducing some form of universal, dynamic road pricing or a road fuel duty as discussed earlier.

For other actors, particularly consumers and leasing companies, ULEVs do not represent disruptive change as "a car is still a car" *in most respects*. Range anxiety and longer recharging times are considered to be short term barriers that are expected to be overcome in the short to medium term. Note no significant advances in and mass uptake of shared mobility and automation[13] was assumed – the other two major innovations that have disruptive potential (Sprei, 2018).

We also expect a 'lack of disruption' for local government (key actor in delivering charging infrastructure) and wider civil society, with gradual air quality improvements in the second half of the assessment period, even in the most stringent scenarios.

[13] The two other so-called transport revolutions, Connected and Autonomous Vehicles and shared mobility, were considered but ultimately excluded from the analysis in order to keep the paper focussed on legislative bans and the phasing out of fossil fuel technology. Further work is underway to examine the combined effects of all three aspects.

Figure 8: Mapping the fossil fuel ban policies onto the disruption framework



5. Conclusion and Policy Implications

This paper set out to explore the implications of the scale and speed of change via technical substitution of the car and van fleet and contrasts this with wider social and lifestyle change through the lens of 'disruption'. It used prospective scenario analysis and an established modelling tool to represent and explore 'disruptive' change in a transport energy system and to explore scenarios of disruptive and more incremental change in decarbonising car and van based transport in the UK.

The IPCC SR15 scenarios showed that with a one-in-two to two-in-three chance of keeping global warming below 1.5°C, emissions need to be reduced to around half their present level by 2030 (and zero by 2050) (Allen, 2019; IPCC, 2018). The transport sector has a mammoth task ahead if this challenge is to be taken seriously across all sectors of the economy. For cars and vans, the scenario modelling shows that existing policy and the R2Z ban may neither hit the target nor make the early gains needed for a 1.5°C trajectory, suggesting that the 2040 target for phasing out ICE vehicles may be inadequate and not fit for purpose. The paper demonstrates that deep reductions in carbon and air quality emissions can be achieved by more ambitious but largely non-disruptive change, with a stronger policy signal of a 2030 ban that includes (plug-in) hybrids. This would provide certainty to manufacturers to invest and innovate, backed up by much improved market conditions for EVs. **The 2040 date should therefore be brought forward, include hybrids and be linked to accelerated investment in charging networks and battery development and deployment.**

In addition, **much more emphasis in policy and strategy development should be put on travel demand reduction and the role of lifestyle change.** This is starting to happen at both global (IPCC, 2018) and national (CCC, 2019b; Hopkinson and Sloman, 2019b; Marsden et al., 2018) levels. But given the scale and pace of change needed much more should be done; the paper has shown how by demonstrating that lower demand for mobility could not only achieve earlier and bigger carbon reductions but also reduce life cycle emissions that are difficult to tackle by technical substitution alone (Anable and Goodwin, 2019). **With increasing road transport electrification, a move towards widening the scope of emissions types and considering the use of life cycle emissions (that account for direct and embedded emissions) in policy making is recommended.** In practice, policy guidance could be updated by providing a revised set of life cycle emissions factors for transport operations and travel activity, building on existing guidance such as in the UK (BEIS, 2019b).

In addition to technical substitution, demand reduction and lifestyle changes would also achieve congestion relief, less parking infrastructure and road expansions, less inequality and improved road safety. It would be able to improve traffic congestion, reduce costs and transport inequality, and enable more active lifestyles. This sends a clear message to policy to tackle all elements of the 'Avoid-Shift-Improve' (Schipper and Marie-Liliu, 1999) hierarchy.

As cars and vans are somewhat easier to decarbonise than other subsectors of the transport energy system (e.g. aviation, long distance freight), **further and earlier 'disruptions' will be needed**. These may include: access bans for high energy/carbon vehicles in urban areas; regulate to reduce the availability and sales of large cars (incl. SUVs, currently a growing market) (Anable and Goodwin, 2019); on-road fuel efficiency programme including speed limiters and incentivization (e.g. insurance) of eco-driving techniques; equitable carbon quotas or allowances (Vaughan, 2019); and universal and dynamic road pricing (not just in urban areas) (Adam and Stroud, 2019; UK House of Commons, 2019). In the longer run, the coordination of transport, planning and ICT objectives should be incentivised to reduce the need to travel (Anable and Goodwin, 2019).

The evolving transition of the proposed bans as well as transformation of mobility patterns due to lifestyle change over a 30-year timeframe are unlikely to be disruptive, as the transport and energy system would on the whole be able to adapt and change. However, **there are some areas that need careful policy design and compensating measures that demonstrate the benefits of the transformation** – an important point that is relevant to all jurisdictions that have implemented, announced or are thinking of introducing bans across the globe. Fuel taxes are an obvious source of political disruption, which have been unpredictable in the past. For the UK, the introduction of **dynamic road pricing (where charges vary by time of day and location) may be needed to sustain £billions of fuel duty revenues, curb travel demand and tackle congestion.** Other aspects might also generate disruptive political forces, e.g. conflict over cycling and EV infrastructure; changes to parking rules that favour shared and/or electric mobility; eventual withdrawal of tax exemptions for ULEVs; and rural-urban divides in the adoption of/access to subsidised cleaner technologies. Some incumbent car manufacturers could be left behind by the shift to electric vehicles, along with the large number of small firms specialising in maintenance and repairs. So, **careful policy design, adaptive policy making, targeted investment (e.g. battery RD&D) and hypothecation of taxes to improve alternatives to fossil fuel mobility** will be essential to minimise political and economic risks.

Acknowledgements

The research for this paper was undertaken as part of the UK Energy Research Centre research programme. CB, JA, IK and JW received funding by the UK Research Councils (award EP/L024756/1). We sincerely thank the anonymous reviewers whose comments and suggestions helped improve and clarify this manuscript.

References

Adam, S., Stroud, R., 2019. A road map for motoring taxation, accessed at https://www.ifs.org.uk/publications/14407 on 13 Jan 2020, in: Emmerson, C., Farquharson, C., Johnson, P. (Eds.), IFS Green Budget 2019. Institute for Fiscal Studies, London.

AEA Technology, 2009. Market outlook to 2022 for battery electric vehicles and plug-in hybrid electric vehicles, Final Report to the Committee on Climate Change, ED46299. AEA Technology, Didcot.

Allen, M., 2019. Why protesters should be wary of '12 years to climate breakdown' rhetoric, accessed at https://theconversation.com/why-protesters-should-be-wary-of-12-years-to-climate-breakdown-rhetoric-115489 on 20/06/2019. The Conversation.

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

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

BEIS, 2018. Digest of UK Energy Statistics (DUKES): energy. Department for Business, Energy and Industrial Strategy, London.

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

BEIS, 2019b. Greenhouse gas reporting: conversion factors 2019, accessed at https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019 on 12 Nov 2019. Department for Business, Energy & Industrial Strategy, London.

BEIS, 2019c. UK becomes first major economy to pass net zero emissions law, Press Release 27 June 2019. Department for Business, Energy & Industrial Strategy, London.

BP, 2019. BP Energy Outlook: 2019 edition, last accessed at https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf on 27/03/2019. BP p.l.c., London.

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., Anable, J., Morton, C., 2019a. Lifestyle, efficiency and limits: modelling transport energy and emissions using a socio-technical approach. Energy Efficiency 12, 187–207.

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. UK Energy Research Centre, London, 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. Transp. Res.: Part A: Pol. Practice 49, 132-148.

Brand, C., Cluzel, C., Anable, J., 2017. Modeling the uptake of plug-in vehicles in a heterogeneous car market using a consumer segmentation approach. Transp. Res.: Part A: Pol. Practice 97, 121-136.

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

BVRLA, 2019. Road to Zero: time to shift gear on tax, last accessed at https://www.bvrla.co.uk/uploads/assets/uploaded/6bdabd12-aa8a-4888-983e74f020402032.pdf on 06/03/2019. British Vehicle Rental & Leasing Association, Amersham.

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

CCC, 2018a. Government's road to zero strategy falls short, CCC says. CCC Press Release, 10 July 2018. https://www.theccc.org.uk/2018/07/10/governments-road-to-zero-strategy-falls-short-ccc-says/ Accessed 20 December 2018. Committee on Climate Change, London.

CCC, 2018b. Letter to Chris Grayling and Greg Clark – assessment of the Road-to-Zero Strategy, 11 October 2018, accessed at https://www.theccc.org.uk/publication/letter-to-chris-grayling-and-greg-clark-assessment-of-the-road-to-zero-strategy/ on 17/07/2019. Committee on Climate Change, London.

CCC, 2018c. Reducing UK emissions – 2018 Progress Report to Parliament. Committee on Climate Change, London.

CCC, 2019a. Net Zero – Technical Report, last accessed at https://www.theccc.org.uk/publication/net-zero-technical-report/ on 20/05/2019. Committee on Climate Change, London.

CCC, 2019b. 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. Committee on Climate Change, London.

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nature Climate Change 8, 268-271.

Defra, 2019. Clean Air Strategy 2019, accessed at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770715/clean-air-strategy-2019.pdf on 02/08/2019. Department for Environment, Food and Rural Affairs, London.

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

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. Department for Transport, London.

DfT, 2018a. Reducing emissions from road transport: Road to Zero Strategy, last accessed at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/739460/road-to-zero.pdf on 22/01/2019. Department for Transport, London.

DfT, 2018b. Transport Statistics Great Britain: 2018 Edition, accessed at https://www.gov.uk/government/collections/transport-statistics-great-britain on 05/09/2019. Department for Transport, London.
DfT, 2019. Vehicle licensing statistics: 2018, accessed at https://www.gov.uk/government/statistics/vehicle-licensing-statistics-2018 on 12 Jan 2020. Department for Transport (DfT), London.
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. RAND Europe, Crown Copyright, Cambridge.
EEA, 2012. COPERT 4 (COmputer Programme to calculate Emissions from Road Transport), last accessed at http://emisia.com/content/copert-documentation on 20/02/2018. European Environment Agency, Copenhagen.
EEA, 2017. COPERT 5.1, last accessed at http://emisia.com/products/copert/copert-5 on 16/04/2018. European Environment Agency, Copenhagen.
HM Treasury, 2018. Budget October 2018. HM Treasury, London.
Hopkinson, L., Sloman, L., 2019a. Getting the Dept. for Transport on the right track. Briefing for Friends of the Earth. Transport for Quality of Life, for Friends of the Earth, London.
Hopkinson, L., Sloman, L., 2019b. More than Electric Cars: Why we need to reduce traffic to reach carbon targets. Briefing for Friends of the Earth, accessed at https://policy.friendsoftheearth.uk/sites/files/policy/documents/2019-01/More_than_electric_cars_final.pdf on 17/07/2019. Friends of the Earth, London.
House of Commons, 2018. Electric vehicles: driving the transition, Fourteenth Report of Session 2017–19, https://publications.parliament.uk/pa/cm201719/cmselect/cmbeis/383/383.pdf, last accessed 10/01/2019. House of Commons Business, Energy and Industrial Strategy Committee, London.
Howard, R., Rooney, M., Bengherbi, Z., Charlesworth, D., 2017. Driving Down Emissions: How to clean up road transport?, last accessed at https://policyexchange.org.uk/wp-content/uploads/2017/06/Driving-down-emissions-How-to-clean-up-road-transport.pdf on 21/01/2019. Policy Exchange, London.
ICO, 2006. ISO 14040: Environmental management - Life cycle assessment - Principles and framework. International Organisation for Standardisation (ISO), Geneva.
IEA, 2011. Energy Technology Perspectives 2010, World Energy Outlook 2011. International Energy Agency (IEA), Paris, France.
IEA, 2015. Energy and Climate Change: World Energy Outlook Special Report. International Energy Agency, Paris.
IEA, 2018. CO2 emissions from fuel combustion. Overview. International Energy Agency, Paris.
IPCC, 2018. Global Warming of 1.5°C, Special Report. Last accessed in October 2018 at: http://www.ipcc.ch/report/sr15/. Intergovernmental Panel on Climate Change, Geneva.
Kay, D., Hill, N., Newman, D., 2013. Powering Ahead: The future of low-carbon cars and fuels. Ricardo-AEA for the RAC Foundation and UKPIA, London.
Köhler, J., Whitmarsh, L., Nykvist, B., Schilperoord, M., Bergman, N., Haxeltine, A., 2009. A transitions model for sustainable mobility. Ecol. Econ. 68, 2985-2995.
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. Commission on Travel Demand, Leeds.
Morgan, S., 2019. EU agrees on 37.5% CO2 reduction for cars by 2030, last accessed at https://www.euractiv.com/section/transport/news/eu-agrees-on-37-5-co2-reduction-for-cars-by-2030/ on 10/03/2019. Euractiv, Brussels.
Odeh, N., Hill, N., Forster, D., 2013. Current and Future Lifecycle Emissions of Key „Low Carbon" Technologies and Alternatives, Final Report. Ricardo AEA for the Committee on Climate Change, Harwell, UK.
OLEV, 2013. Driving the Future Today - A strategy for ultra low emission vehicles in the UK. Office for Low Emission Vehicles, London.
OLEV, 2018. Low-emission vehicles eligible for a plug-in grant, last accessed at https://www.gov.uk/plug-in-car-van-grants on 20/02/2019. Office for Low Emission Vehicles, London.
Palmer, J., Schwanen, T., 2019. Clearing the air after "dieselgate": Time for European regulators to experiment with participatory governance. The Geographical Journal 0.
Pehl, M., Arvesen, A., Humpenöder, F., Popp, A., Hertwich, E.G., Luderer, G., 2017. Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. Nature Energy 2, 939-945.
Plötz, P., Funke, S.Á., Jochem, P., 2018a. Empirical Fuel Consumption and CO2 Emissions of Plug-In Hybrid Electric Vehicles. J. Ind. Ecol. 22, 773-784.
Plötz, P., Funke, S.Á., Jochem, P., 2018b. The impact of daily and annual driving on fuel economy and CO2 emissions of plug-in hybrid electric vehicles. Transp. Res.: Part A: Pol. Practice 118, 331-340.
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. Nature Energy 2, 17024.
Quarmby, S., Santos, G., Mathias, M., 2019. Air Quality Strategies and Technologies: A Rapid Review of the International Evidence. Sustainability 11.
Rahmstorf, S., 2019. Simple emissions budget calculator, Blog article: http://www.realclimate.org/index.php/archives/2019/08/how-much-co2-your-country-can-still-emit-in-three-simple-steps/.
Reiter, C., Parkin, B., 2019. VW Boosts Electric-Car Target by 50% With Budget, China Models, last accessed at https://www.bloomberg.com/hyperdrive on 03/03/2019, Bloomberg. Bloomberg.
Rodríguez, F., Bernard, Y., Dornoff, J., Mock, P., 2019. Recommendations for post-Euro 6 standards for light-duty vehicles in the European Union, accessed at https://theicct.org/sites/default/files/publications/Post_Euro6_standards_report_20191003.pdf on 13/01/2020. International Council on Clean Transportation, Berlin.
Schipper, L., Marie-Liliu, M., 1999. Flexing the link between transport greenhouse gas emissions: a path for the World Bank. International Energy Agency, Paris.
Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., Meza, M.J.F., Fulton, L., Kobayashi, S., O., L., McKinnon, A., Newman, P., Ouyang, M., Schauer, J.J., Sperling, D., Tiwari, G., 2014. Transport, in: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., Stechow, C.v., Zwickel, T., Minx, J.C. (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 University Press, Cambridge, United Kingdom and New York, NY, USA.

Smith, A., Stirling, A., Berkhout, F., 2005. The governance of sustainable socio-technical transitions. Res. Pol. 34, 1491-1510.
SMMT, 2018. New Car CO_2 Report 2018: The 17th report. The Society of Motor Manufacturers and Traders (SMMT), London.
Sprei, F., 2018. Disrupting mobility. Energy Research & Social Science 37, 238-242.
Statistics Netherlands, 2016. Transport and mobility 2016. Statistics Netherlands, The Hague/Heerlen/Bonaire.
UK Energy Research Centre, 2019. Review of Energy Policy 2019, accessed at file:///C:/Users/cbrand/Downloads/UKERC_Review_Energy_Policy_19.pdf on 06 Jan 2020. UK Energy Research Centre, London.
UK House of Commons, 2019. Transport Committee to kickstart conversation on national road pricing, accessed at https://www.parliament.uk/business/committees/committees-a-z/commons-select/transport-committee/news-parliament-2017/national-road-pricing-17-19/ on 13 Jan 2020. UK House of Commons, London.
Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28, 817-830.
Unruh, G.C., 2002. Escaping carbon lock-in. Energy Policy 30, 317-325.
Unruh, G.C., Carrillo-Hermosilla, J., 2006. Globalizing carbon lock-in. Energy Policy 34, 1185-1197.
Vaughan, A., 2019. Electric cars won't shrink emissions enough – we must cut travel too, accessed at https://institutions.newscientist.com/article/2197211-electric-cars-wont-shrink-emissions-enough-we-must-cut-travel-too/ on 17/07/2019, New Sci. New Scientist, London.
Whelan, G., 2007. Modelling car ownership in Great Britain. Transp. Res.: Part A: Pol. Practice 41, 205-219.
Williams, M.L., Lott, M.C., Kitwiroon, N., Dajnak, D., Walton, H., Holland, M., Pye, S., Fecht, D., Toledano, M.B., Beevers, S.D., 2018. The Lancet Countdown on health benefits from the UK Climate Change Act: a modelling study for Great Britain. The Lancet Planetary Health 2, e202-e213.
WorldAtlas, 2018. Countries That Will Ban Gasoline Cars, 19 December 2018, last accessed at https://www.worldatlas.com/articles/countries-that-will-ban-gasoline-cars.html on 23/02/2019. WorldAtlas.com.
Yuan, J., Xu, Y., Hu, Z., 2012. Delivering power system transition in China. Energy Policy 50, 751-772.
Zachariadis, T., Ntziachristos, L., Samaras, Z., 2001. The effect of age and technological change on motor vehicle emissions. Transp. Res.: Part D: Transport Environ. 6, 221-227.