

# Deep Cuts: Achieving Transport Energy Demand Reductions for Climate and Health Co-Benefits

## Authors

Brand, C.<sup>1,6,\*</sup>, Marsden, G.<sup>2,6</sup>, Anable, J.L.<sup>2,6</sup>, Dixon, J.<sup>3,4,6</sup>, Barrett, J.<sup>5,6</sup>

## Affiliations

<sup>1</sup> Environmental Change Institute, University of Oxford, South Parks Road, Oxford, OX1 3QY, United Kingdom.

<sup>2</sup> Institute for Transport Studies, University of Leeds, 34-40 University Road, Leeds, LS2 9JT, United Kingdom.

<sup>3</sup> Transport Studies Unit, University of Oxford, South Parks Road, Oxford, OX1 3QY, United Kingdom.

<sup>4</sup> Civil & Environmental Engineering, University of Strathclyde, 75 Montrose Street, Glasgow, G1 1XJ, United Kingdom.

<sup>5</sup> Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, United Kingdom.

<sup>6</sup> Centre for Research into Energy Demand Solutions, South Parks Road, Oxford, OX1 3QY, United Kingdom.

\* Corresponding author

## Abstract

The transport sector is a crucial yet challenging area to decarbonize, given its heavy reliance on fossil fuel usage, carbon-intensive infrastructure, and car-centric lifestyles. It remains the largest contributor to local air pollution in cities yet has the potential to improve our physical and mental health. Here we assess the carbon emission impacts, co-benefits and policy deliverability of energy demand reductions in the transport sector. Using a comprehensive bottom-up modelling framework, we provide an integrated oversight of the impacts of deep mobility-related energy demand reductions, including lifecycle carbon emissions, local air pollution and health impacts. Using the UK as a case study, our analysis reveals that energy demand reductions of up to 61% by 2050 compared to baseline levels are achievable and can enhance citizens' quality of life. Business as usual approaches which rely on a technical transition miss the legislated carbon budgets and result in higher energy demand in 2050. More comprehensive scenarios deliver a reduction of up to 72% in total lifecycle carbon emissions by 2050 compared to 2020 levels, with approximately half of the reduction achieved through mode shifting and avoiding travel, while the other half comes from vehicle energy efficiency, electrification, and downsizing of the vehicle fleets. We show that it can lead to significant co-benefits such as reduced local air pollution and improved public health. We discuss deliverability of policy measures and integrated strategies needed for achieving deep transport-energy demand reductions.

## Highlights

- Comprehensive bottom-up modelling framework of energy demand reduction in transport
- Without balanced pathways the UK will not meet its climate and air quality targets
- Energy demand reductions of more than half compared to baseline levels are achievable
- Shifting and avoiding travel and moving goods can contribute half of these reductions
- Large co-benefits for improved public health and reduced local air pollution

## Keywords

Transportation energy; Energy demand; Scenario modelling; Pathways; Co-benefits; Air pollution; Health impact assessment

## Abbreviations

BAU                      Business-as-usual, scenario name

CAFÉ	Corporate Average Fuel Efficiency (USA)
CO <sub>2</sub>	carbon dioxide
COP	Conference of the Parties, decision making body of the UNFCCC
EV	Electric vehicle
FCEV	Fuel cell hydrogen electric vehicle
GHG	Greenhouse gas
HA	High Ambition, scenario label
HEV	Hybrid electric vehicle
HGV	Heavy goods vehicle
ICE	Internal Combustion Engine
IPCC	Intergovernmental Panel on Climate Change
LED	Low Energy Demand
PHEV	Plug-in hybrid electric vehicle
SUV	Sports Utility Vehicle
TC	Transformative Change, scenario label
TEAM-UK	Transport Energy and Air pollution Model, UK version
ULEV	Ultra low emission vehicle
UNFCCC	United Nations Framework Convention on Climate Change
WHO 'HEAT'	World Health Organization 'Health Economic Assessment Tool for walking and cycling'
ZEV	Zero (tailpipe) emission vehicle
ZEVM	Zero Emission Vehicle Mandate, announced by UK Gov't Oct 2023

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# 1 Introduction

## 1.1 Why we need to talk about transport-energy demand reductions

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, resulting in a 60% increase in transport carbon dioxide (CO<sub>2</sub>) emissions compared to 2015 levels [1]. With the sector heavily reliant on oil, it currently accounts for 21% of global carbon emissions and has become the largest emitting sector in many developed countries [2]. It is the fastest-growing energy end-use sector in various parts of the world [1]. Although Europe and North America have historically been the main contributors to transport emissions, projected emission growth is expected to be concentrated in Asia.

Deep cuts in emissions requires the transformation of the whole transport system, including tackling how often and how far we travel and move goods. It requires a combination of measures such as fuel efficiency improvements, fuel switching, modal shifts, and a reduction in transport demand [1, 3]. 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 current decade would see CO<sub>2</sub> emissions from cars drop by only 14% by 2030 compared with 2018 [4]. One reason for this is that even if all new cars were electric from today, it would still take 15-20 years to replace the world's fossil fuel cars [5]. Some of the other measures can be implemented overnight, such as fossil fuel taxes and zero (tailpipe) emission vehicle incentives or mandates. A high quality cycle network for a city can be built in 3 years. But others are slower or require international cooperation, such as for international road freight and aviation, with international agreements on, say, fuel taxes and route optimisation taking decades to materialise. Other options, such as road-space reallocation [6] and higher fossil fuel taxes for road use [7] have met resistance, resulting in politicians shying away from implementing them. Overcoming this resistance is at least partly overcome by implementing a combination of complementary policies in a sequence that allows a fair and acceptable transition.

The discourse on transport decarbonisation and improving local air quality and public health has largely overlooked the crucial role of energy demand for mobility [8-11]. Technological advances alone are now understood not to be capable of delivering emissions reductions fast enough [1, 12]. For cars in the UK, for instance, it has been *“mathematically possible”* to reduce *tailpipe* emissions fast enough to meet the legislated 6<sup>th</sup> carbon budget of 2033-2037, but *“the pace of migrating the parc away from internal combustion needs to be dramatic in terms of both the registration of new battery electric cars coming into the parc and the departure of internal combustion engine models”* [13]. The UK Government announced in October 2023 a ‘Zero Emission Vehicle Mandate’ (ZEV), which requires 80% of new cars and 70% of new vans sold in Great Britain to be zero tailpipe emission by 2030, increasing to 100% by 2035 [14]. This falls well short of the ‘mathematically possible’ pathway that would be compliant with the 6<sup>th</sup> carbon budget [12].

Global efforts such as the COP26 presidency programme focused entirely on road-transport electrification [15]. While the transition to electric or hydrogen (H<sub>2</sub>) vehicles would allow the sector to decarbonise at the tailpipe (or direct, at source), life-cycle emissions from electric or H<sub>2</sub> vehicles are significant and depend heavily on the kind of electricity, primary fuel (e.g., natural gas for H<sub>2</sub>), battery and materials used. Any holistic analysis on the benefits of shifting to electric needs to consider increased generation, transmission and storage capacity, posing strains on power networks and grid overloading risks unless appropriately planned and invested in [16-18]. Furthermore, the challenges extend beyond cars and light goods vehicles (vans), as air travel and heavy goods transport can only be partially electrified. When looking beyond transport to other sectors transitioning to electricity, such as domestic heat [19], the cumulative demand for additional electricity could necessitate an electricity system four times larger than the current one [2].

Whilst there are arguments that scaling up grid provision is technically feasible it is far from clear how this will be paid for and by whom. If we take the example of EVs in the UK, then 23% of households do not own a car and so ‘socialising’ the cost of grid upgrades through electricity bills would be deeply inequitable. General taxation might be more appropriate but the politics are difficult as has been revealed during recent energy price spikes following the Russian invasion of Ukraine.

It is important to recognize that road transport electrification does not address other pressing concerns such as traffic congestion, physical inactivity, emissions of fine and ultrafine particulate matter from tyre wear and road surface abrasion, and road safety [20]. EVs 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 [21], especially in the developing world where e-cars may well only be an option for the powerful and wealthy.

Traffic remains the largest contributor to both poor air quality and associated mortality in Europe [22] and . A car is a car is a car, however it is propelled [23]. While air quality and climate emissions may improve, cheaper electric motoring could introduce new challenges such as increased rates of traffic growth [24]. For a range of high EV uptake scenarios, for example, the UK Government's own Road Traffic Forecasts projects traffic growth to rise between an increase of 11% and 54% by 2060. So, again, while electrification and a decarbonised supply are important they may well not be sufficient or fast enough [25]. The carbon reduction debate therefore seems to have reached a point where it is accepted that both technological transformation and demand reductions and shifts are necessary to reach the goals set by the UNFCCC (United Nations Framework Convention on Climate Change). That still leaves significant questions as to what the impacts and benefits or challenges different mixes would generate.

## 1.2 Aims and contribution

This paper addresses the central question: what is the contribution that energy demand reduction in transport can make to direct and lifecycle carbon emissions, local air pollution and health impacts? It then goes 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 impacts and policy deliverability of the changes required. Using the UK as a case study, the paper aligns with previous findings that reaching 2030, 2035 or 2050 carbon targets would be impossible without significant reductions in energy demand for mobility [see e.g. 1, 12, 26, 27, 28].

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 [29-31] of *avoiding* travel in the first place (trip reduction due to change in activity or distance reduction due to changes in destinations) 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 (IPCC) [32] and the framing and analysis of *Demand, Services and Social Aspects of Mitigation* (Chapter 5) in the Sixth Assessment Report of the IPCC [33].

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 while being costly and risky, and that policies influencing the demand for travel and mode switching should have a more prominent role [2, 27]. 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.

Our scenario development began by exploring achievable outcomes with existing technologies and current social and political contexts. Policy levers, such as frequent flyer levies, increased taxation on multi-car ownership, and improved provisions for walking, cycling, and zero-carbon public and shared mobility, were deemed plausible so long as they had been hitherto applied at some scale in similar socio-political contexts to the UK or their implementation had been modelled and subjected to some degree of public and political scrutiny. For example, research shows that a Frequent Flyer Levy or Frequent Airmiles Tax can be both progressive and fair, and be popular with the public, although the framing and messaging around such policies are likely to be crucial [34]. These policies were assumed to achieve change particularly in the crucial 2020s and existing evidence used to quantify feasible shifts in the number of journeys, travel distances for different purposes, and transport modes. Significant freight consolidation, improved load factors, and better on-road fuel efficiency were also necessary. Electrification remains central but with fewer and smaller vehicles that are more intensively used.

Using a comprehensive national bottom-up modelling framework, we provide a novel integrated assessment of the benefits of deep mobility-related energy demand reductions, including lifecycle carbon emissions, local air pollution and health impacts. This paper presents the extent to which our ambitions have pushed the energy and carbon boundaries for mobility. What distinguishes this

scenario exercise is the creation of an optimistic and plausible [35] vision of a life with lower energy demand. It entails substantial and radical changes but offers a positive perspective on maintaining a good quality of life while reducing costs for society as a whole [36]. People can still access local services, leisure activities, and diverse employment opportunities, while enjoying cleaner air and improved mental and physical health.

The paper proceeds as follows. Section 2 provides the policy background to the UK case study, highlighting the rationale for focussing on a global north economy that struggles to decarbonise the sector. Section 3 then describes the scenario and modelling approach that we adopted to construct the LED scenarios, including the development of the LED narratives and how these were translated into integrated, balanced modelling pathways. Section 4 presents the main findings structured around assessments of changes to mobility-related energy demand, direct and lifecycle carbon emissions, the demand for transport and mobility, local air pollution and public health. The final two Sections discuss what policies and strategies might deliver the pathways before concluding with the main contributions of this work.

## 2 Background – the UK case study

In the UK, road transport accounted for three quarters (75%) of transport energy consumption in 2022, with the remainder almost entirely from domestic and international air travel (21%) [37]. Of the road component, fuel consumption from cars accounted for more than half (54%), with the remainder coming from heavy goods vehicles (HGVs) (20%), light goods vehicles (vans) (7%) and buses (2%). Energy use from transport has *increased* by 5% since 1990 against a UK economy-wide *decrease* of 10% and remains 95% dependent on fossil fuels (the remainder is bioenergy, waste and electricity) (ibid). COVID-19 had a major effect in 2020 and 2021, with transport energy use decreasing by 28% between 2019 and 2020 [37]. In 2022, energy use was still 11% lower than in 2019, mainly for road and aviation.

Transport has grown as a share of overall greenhouse gas (GHG) emissions with a *net increase* of 4% between 1990 and 2022 *vis-à-vis* a *decrease* of 45% for all sectors combined [38]. It is by far the largest emitting sector (34% of total GHG emissions, followed by energy supply at 19% and business).

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 [21]. A recent whole of government analysis of the likely pathway from current and planned policies which allow for such growth coupled with electrification tracks some 224 MtCO<sub>2</sub>-e above the pathway set out in the agreed 6<sup>th</sup> carbon budget [39]. To put this in context, the difference in annual surface transport emissions between 2019 and 2020, where the UK had substantial COVID-19 related periods of lockdown, was 24 MtCO<sub>2</sub>-e [38]. Business as usual planning continues in the face of clear and consistent evidence that this will fail in climate policy terms as well as in congestion terms [12, 24].

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 (tailpipe) emission vehicles (ZEVs)<sup>1</sup>, primarily through electrification. A lack of progress with heavy goods vehicles and aviation persists, but the unexpected change was the increase in new car energy consumption and CO<sub>2</sub> between 2016 and 2019 [40]. Switching from diesel accounted for a small proportion of this increase; the main culprit was a continued swing towards larger passenger cars, particularly Sports Utility Vehicles (SUV), which use about 15% more energy than their hatchback or sedan equivalents [4]. Electric vehicles accounted for 23% of sales in 2022 [40] (up from 2.5% in 2019), with 6.3% sold being plug-in hybrid electric vehicles (PHEVs). PHEVs have shown to perform only a 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 [41]. This gap between declared vehicle performance and real-world results prevails across all vehicle types and technologies. For new cars, fleet average NEDC test cycle data (now replaced by the WLTP test

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<sup>1</sup> The UK definition of ULEVs include BEVs, PHEVs and FCEVs that produce <75 gCO<sub>2</sub> per vehicle-km under the existing test cycle. ZEVs emit no carbon or local air pollution from the tailpipe and include BEVs and FCEVs. Strictly these are only zero emission when powered by renewable or zero emission electricity.

cycle, which is not directly comparable) suggest a 29% reduction in tailpipe CO<sub>2</sub> between 2000 and 2019 [40]. 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 and has effectively negated any reported savings from efficiency improvements over the past decade [42].

In sum, beyond the UK Government's focus on transport electrification, the scientific literature is clear that reducing energy consumption and emissions from transport requires a combination of approaches, including a shift away from car-dependent lifestyles [43]; the development of more compact and mixed-use urban environments that offer a range of services and amenities within walking or cycling distance [44]; and the integration of land use and transport policies that prioritize walking, cycling, and public transport as the backbone of urban transport [45]. Such a comprehensive approach will require political will, focus and communication on the multiple benefits beyond carbon reduction, targeted and repurposed investment, public support, and collaboration across multiple sectors and stakeholders. Despite there being evidence of other approaches that could make a difference, these often seem to be dismissed by the UK Government as insufficient or ineffective when we have not really tried to deploy them seriously or at scale [12]. A more balanced approach between demand and supply options underpins the development of the UK LED scenarios which are described next.

### **3 A national modelling framework for transport-energy demand reduction**

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.

#### **3.1 Scenario building using coherent storylines**

Our scenario approach is attempting to give insights into the possible scale of change in energy demand, carbon emissions, local air pollution (focussing on ultra-fine particulate matter, PM<sub>2.5</sub> and nitrogen oxides, NO<sub>x</sub>) and public health (physical activity, air pollution exposure, crash risks) under certain circumstances. We have developed three scenarios (the LED scenarios from hereon), which are:

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 announcements and 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.

Here, the Avoid-Shift-Improve hierarchy has been used to emphasise the priority ordering and layering of our scenario storylines that stand apart from the dominant supply and vehicle technology-oriented approach to energy demand reduction and decarbonisation in the sector [46].

As strategies to *avoid* travel demand and car ownership, the LED scenarios considered ways to 'lock-in' recent demand changes, some of which started well before the COVID-19 pandemic [47], new regulatory frameworks to steer emergent transport innovations, the promotion of 'car clubs' [48] and freight consolidation centres [49], 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.

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 [47, 50]. 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’ [51].

To avoid ‘induced travel’ from emerging innovations [52, 53] 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 [53], 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.

As strategies to *shift* travel to the most sustainable modes, we considered 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.

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. This is supported by evidence that suggests that the trajectory for urgent CO<sub>2</sub> 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 [27, 54].

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.

Table 1 lists the key assumptions underpinning the three scenarios.

**Table 1: Key assumptions underpinning the three scenario storylines**

<b>BAU scenario</b>	
<ul style="list-style-type: none"> <li>• Projection of transport demand, supply, energy use and emissions as if there were no changes to firmly committed and actioned transport and energy policy. Policy announcements and ambitions without firm actions have no measurable impact.</li> <li>• Ageing population – BAU takes into account changes to trip rates and distance travelled of an ageing population. For instance, an older person makes very few work or education trips – just 24 trips per person per annum on average, less than 3% of their total annual trips. Retired people initially tend to make more leisure trips, but as they become older and disabilities intervene, trip making tails off. National Travel Survey data show there was a decline in the average number of shopping trips per capita until recently (from 230 trips to 189 trips since 1995/98 =18% in 20 years but only 1% in past 5 years). The recent slowdown is likely related to the fact that there has been a major uptick in short journeys for all purposes. However, distance travelled for shopping has not increased.</li> <li>• Phase out sale of conventional fossil fuel cars and vans by 2040.<sup>2</sup> Consumers increasingly shy away from diesels post ‘Dieselgate’ [55]. Existing UK plug-in vehicle grant for cars, vans, taxis and motorcycles (up to £3,500 for cars, depending on year and how ‘plugged-in’ the vehicle is) to ‘phase out’ by the late 2020s. Consumer awareness of EV incentives and make/model availability increases to ~50% by mid 2020s then levels out, simulating reluctance by policy and industry to support the shift to electric. Certainty of access to charging for fleet operations stays at 40%. Private access to overnight charging level at 70%, i.e. the share of households with potential for off-street charging. See Brand et al. [56] for the full set of assumptions of the BAU scenarios.</li> </ul>	

<sup>2</sup> This was 2040 and is now (as of October 2023) 2035, once the legislation is adopted, but was not the case in 2022 when the models were being built.

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## LED scenarios: High Ambition (HA) and Transformative Change (TC)

### Core elements of the storylines

- No more steady incremental changes in travel patterns – Rapid action to reduce *private* car use will be ‘just’ if paralleled by big increases in supply of alternatives (shared mobility, public transport, active travel incl. e-bikes and other micro e-mobility).
- Gradual/rapid 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. Triggered by ‘worsening conditions’ (climate change, pandemic(s), economic downturn), social norms promote status of more sustainable modes of transport and low traffic neighbourhoods and demote single-occupancy car travel, fossil fuelled vehicles, unnecessarily long distances and speeding.
- 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 and ‘proximity principle’ in planning – e.g. local shopping, local schools, local leisure travel.
- Changes in work patterns and business travel fuelled by renewed emphasis on quality of life but also facilitated by increasingly sophisticated ways of substituting disproportionately 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.
- International aviation and shipping included in domestic carbon budget. No use of offsets. But #flyingless results in *more* domestic surface leisure and business travel.
- Fastest reductions achieved by passenger travel to compensate for challenges with freight decarbonisation (HGVs) and travel reduction (hard to decouple from economic activity).
- Much more radical market transformation of passenger vehicle fleet than currently assumed as it will include rapid phase out of sale of high-polluting vehicles.
- Autonomous vehicles by 2050 only in niche local applications and some long distance fixed routes. Limited impact.

### Socio-economic and structural factors (largely external to the transport sector)

- “Non-transport transport factors” (e.g. wider socio-technical and policy shifts) will be as important as transport specific technology and policy change.
- Structure of labour market will result in significant changes to commuting: service and gig economy (=increase), and introduction of a 4 day working week (=reduction) (TC scenario)
- Changes to structure of retail – retail and leisure blend together as more ‘mundane’ shopping is done online but coffee and experience = local leisure
- Businesses are made much more accountable for their emissions (including commuting)
- Devolution/ localisation – changes to planning system and desire to work and play more locally
- Social norms change: single occupancy car use, large cars and flying less acceptable (much less in Transformative scenario)
- Car fleet is reduced substantially as driving licence uptake is down with transition to ‘car usership’
- Public acceptance for new regime of ‘pay as you go’ pricing linked to environmental impacts
- Taxing of aviation (esp. frequent fliers) becomes socially acceptable during the 2020s

### Transport planning and policy

- No more road building or airport capacity expansion; some roads repurposed for shared, public and active mobility
  - No more development on greenfield sites (consistent with the ‘no new homes’ scenario)
  - Integrated transport authorities in all urban/city regions (One network; One timetable; One ticket)
  - Re-regulation of buses and railway under public control
  - Doubling investment in public transport, walking and cycling – including e-bikes and on-demand services enabled by ICT
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- Construction of high-quality cycling networks of segregated cycleways in all urban areas and along all single carriageway roads radiating within e-bike range (about 15km) from major settlements
  - Single occupancy car use becoming socially unacceptable and parking charges and infrastructure designed to encourage vehicle sharing
  - 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)
  - Bus, taxi and shared fleets *increase* – largely electric by 2030, except coaches – as a result of targeted investment, promotion, priority in urban and rural areas and procurement
  - Increase in LCV (van) fleet due to more online shopping – electric only sold from 2030
  - Fossil fuel ICE cars (not vans) banned from urban centres by 2030; all cars banned by 2035
  - Large and heavy ICE, PHEV and HEV cars gradually phased out in 2020s; only BEVs (for cars and vans) from 2030 (2025 in Transformative case), so 5-10 years earlier than current policy [14]
  - Big investment in and standardisation of charging infrastructure across the nation
  - Road freight – much improved logistics, vertical integration eg Amazon – improves load factors for long and medium distance freight
  - HGV – renewed push for consolidation centres around big cities and towns – reduced miles travelled
  - No significant shift 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)
  - Last mile delivery regulated to require zero emission vans or e-cargo bikes
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## 3.2 Modelling low energy demand scenarios

### 3.2.1 The transport-energy-environment systems modelling framework

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). To date, the underlying transport-energy-environment system modelling framework has been applied in a number of prospective scenario [54, 57-60] and policy [61] modelling studies.

A detailed description of the modelling methods is provided in Brand et al. [56]. In sum, 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 [62], 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 economic activity (GDP/capita), population and supply and policy costs. Freight demand is simulated as a function of economic activity, population and freight transport prices, with reference demand elasticities taken from Dunkerley et al. [63]. 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<sup>3</sup> technologies such as increasingly efficient gasoline internal combustion vehicles (ICV), battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and hydrogen (H<sub>2</sub>) 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 PHEV, 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

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<sup>3</sup> 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.).

UK market to develop and invest in these technologies [64]. New vehicle choice is modelled using a hybrid discrete choice and consumer segmentation model, as described in Brand et al. [56, 58]. Vehicle scrappage probabilities<sup>4</sup> were left unchanged for the BAU case, so that the mean car age remained at about 7.5 years, and 6.5 years for vans [see 56 for methods]. Total car ownership is modelled based on established methods [65, 66] 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 ('no car', 'at least 1 car', 'at least 2 cars', 'at least 3 cars' per household).

### 3.2.2 Energy use and emissions

Direct energy use and air pollutant emissions (in tonnes of CO<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, CH<sub>4</sub>, NMVOC, and so on) from motorised travel were computed by using disaggregate sets of emission factors, which were based on the results of large scale vehicle emissions testing programmes. For road transport, speed distributions for each vehicle type (car, motorcycle, LGV/vans, HGV) and road segment type (urban, rural, motorway) were used to calculate energy consumption and emissions, based on average speed-emissions curves developed in previous research and emissions inventories such as HBEFA [67] and supplemented with data from COPERT IV [68] and the UK National Atmospheric Emission Inventory (NAEI) [69]. Non-exhaust emission factors for PM<sub>2.5</sub> from road transport were based on NAEI (ibid.). The approach allowed us to model the combined effects of different fleet compositions, different sets of emission factors (e.g. 'official' vs 'real world'), traffic congestion, cold starts and driver behaviour (e.g. eco-driving, speed limit enforcement). Life cycle energy use and emissions were modelled separately in TEAM as described in [56].

### 3.2.3 Modelling health effects

As an add-on to the transport-energy-environment modelling in TEAM, a limited Health Impact Assessment (HIA) was conducted using the World Health Organization's Health Economic Assessment Tool (HEAT, version 5.2) for walking and cycling to evaluate the health effects resulting from changes in physical activity, air pollution exposure, and crash risks associated with increased walking, cycling, and e-biking in the UK. The assessment considered two time periods: 2019 (baseline) to 2030 (medium term) and 2019 to 2050 (long term). Details of the assessment methods, data sources and assumptions can be found in Kahlmeier et al. [70] and Götschi et al. [71].

## 3.3 Turning scenario narratives into system modelling assumptions

Starting with the storylines, we quantified the LED scenarios by identifying socio-technical and policy levers (e.g., working from home or at a local hub) and their underlying factors (e.g., number of commuting trips and trip lengths). Guided by the three strategic areas of the Avoid-Shift-Improve hierarchy, these factors were used to assess changes in transport demand, vehicle technology supply, regulatory constraints, and the evolution of vehicle fleets out to 2050. Providing the more than 30 levers (e.g. uptake of teleworking) and over 100 factors (e.g. mode shift from car as driver to national rail for trip lengths of 25-50 miles) would be far too long for the main text. But to give the reader a flavour of how this was done, we give two exemplars for each of these strategic areas: for *Avoid* (1) commuting trips and (2) international aviation; for *Shift* (3) mode shift from private car to other modes and (4) from road freight to rail and active mobility; and for *Improve* (5) accelerated fleet decarbonisation and (6) on-road fuel efficiency programmes (including speed limits and eco-driving). In the first example – the case of commuting to/from work or a place of study – we have assumed 25% of the workforce will work at home on some days by 2030 and 40% by 2050 (HA scenario), leading to reduction of trips of 30% on average. So, a further 10% of workforce reducing by at least 30% on average = 3%; further 25% reducing by at least 30% = 7.5%. Or take mode shift, where we assumed different substitution rates varying by trip lengths and modes of travel – e.g. in the 2-5 mile range we assumed a shift from car (as driver) to local bus of 5% (HA) and 10% (TC) in 2030. Details on the rationale, supporting evidence and sources that underpin our assumptions are given in the Supplementary Material SM1.

**Table 2: Selection of six key modelling assumptions for the LED scenarios**

Avoid	High Ambition	Transformative
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<sup>4</sup> The UK car fleet age profile implied a 50% scrappage probability applied for cars that were ~16 years old.

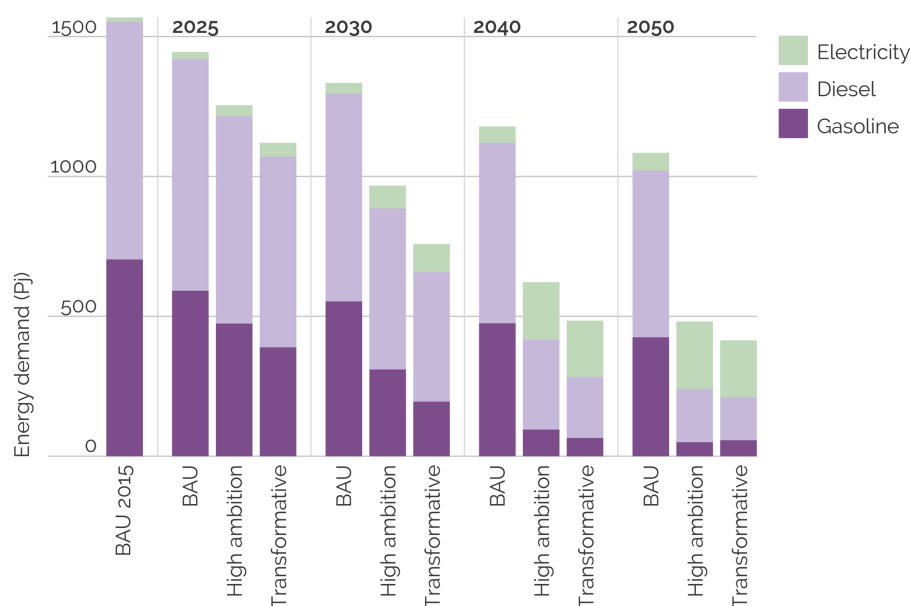
Lever & factor	Rationale and supporting evidence	2030	2050	2030	2050
1. Commuting trips: reduction in trips per person over 2019 due to working at home or in hubs	Industrial restructuring has impact on commuting, incl. telecommuting [72]. Uptake in teleworking is reinforced by tax incentives, travel plans, fast broadband-roll-out (by 2028 in HA, 2024 in TR), workplace parking levies, introduction of a 4-day working week [73] and greater focus on 'quality of life' [74]. No new developments on greenfield sites (to reduce urban sprawl).	-3%	-7.5%	-7.5%	-14%
2. International aviation: reduction in passenger-km over 2019, post-COVID-19	Post-COVID-19 'recovery' happens at different scales and timeframes as changing social norms and pricing policies affect demand profiles, incl. reduced trip rates and destination shifting esp for business travel and some leisure.	-23%	-17%	-43%	-39%
<b>Shift</b>					
3. From private car (as driver or passenger) to other modes	Huge investment in high quality public and shared transport. Renewed 'Go Dutch' active travel strategy via high quality infrastructure, 'slow mode' prioritisation and culture change in urban and suburban areas. No new major road expansions. Repurposing some roads for shared, public, and active mobility. <i>(*) varies by trip length and travel mode</i>	1-20% (*)	2-25% (*)	2-25% (*)	4-30% (*)
4. Freight: from road to rail, and from van to e-cargo bike	National freight demand remains disappointingly inelastic. Limited load capacity of e-cargo bikes and almost exclusive use in urban areas. Assumed large investments in logistics and ICT and renewed push for consolidation centers around big cities and towns to maximize the use of brownfield sites for HGV. Assumed small shift away from road to rail/e-cargo.	3%	6%	5%	10%
<b>Improve</b>					
5. Decarbonisation of vehicle fleets: share of BEV in total car fleet	New internal combustion engine, plug-in hybrid electric vehicle, and hybrid electric vehicle motorcycles, cars, buses, vans and trucks are phased out by 2030 (HA) and 2025 (TC) and replaced with a largely electric fleet	21%	99%	38%	100%
6. On-road fuel efficiency programmes, reduction in energy use per km travelled	Speed limits for cars, vans and motorcycles on motorways are lowered (to 100 kph in TC) and properly enforced. National eco-driving programme. Speed/acceleration limiters become mandatory for HGV, improved & mandatory aerodynamics.	3%	10%	5%	15%

## 4 Results

### 4.1 The UK can more than halve energy demand for mobility relative to current levels

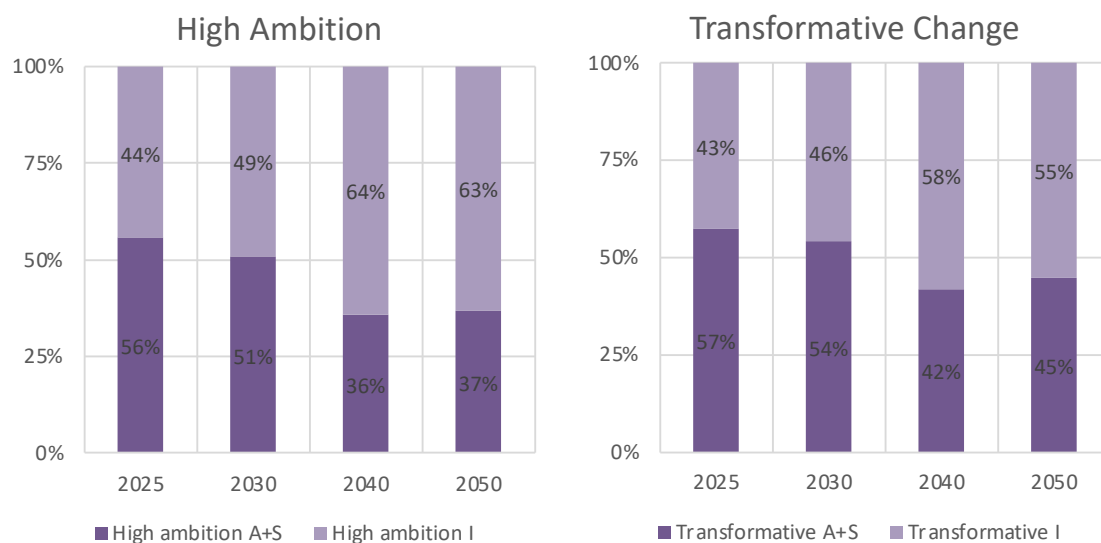
The higher uptake of lower and zero (tailpipe) emission vehicles combined with efficiency gains, mode shifts and significant alterations to work, leisure and shopping travel patterns resulted in final energy demand being more than halved from transport by 2050 in both LED scenarios when compared to the '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 our low energy demand scenario futures we would see early gains being made in the 2020s so that energy demand were 27% (HA) and 43% (TC) lower than BAU already by 2030.

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



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 HA) by 2050 in the low energy demand scenarios. Although an 80% reduction in fossil fuel use is huge, transport in our LED scenarios is still at least 50% fuelled by fossil fuels in 2050, resulting in sizeable residual emissions.

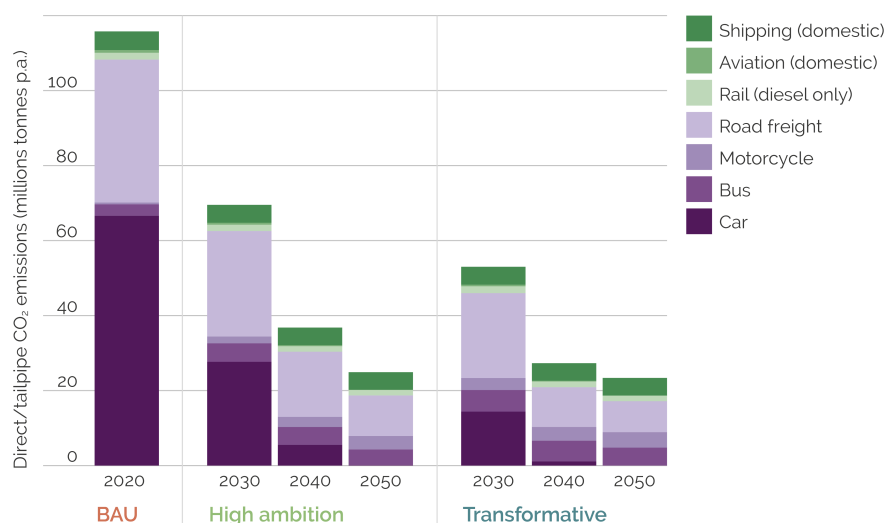
**Figure 2: Contributions of Avoid+Shift (A+S) and Improve (I) components to transport energy reduction (road and rail only). Left panel: High Ambition scenario, Right panel: Transformative Change scenario.**



#### 4.2 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. Direct CO<sub>2</sub> 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, albeit still significant, changes required to the transport or energy system. Residual emissions in 2050 are largely from road freight, shipping and international aviation where decarbonisation options can take longer to take effect (e.g. fleet renewal) or do not cover every locality, industry or user group (e.g. expect rural buses to be HEV into the 2040s, and there remain a significant fleet of long haul HGV that are diesel powered).

**Figure 3: Direct CO<sub>2</sub> emissions (domestic transport, excluding international aviation/shipping)**



The TEAM framework allowed us to further assess lifecycle CO<sub>2</sub>-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 56]. 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 clear improvement to a 25% reduction in the BAU case.

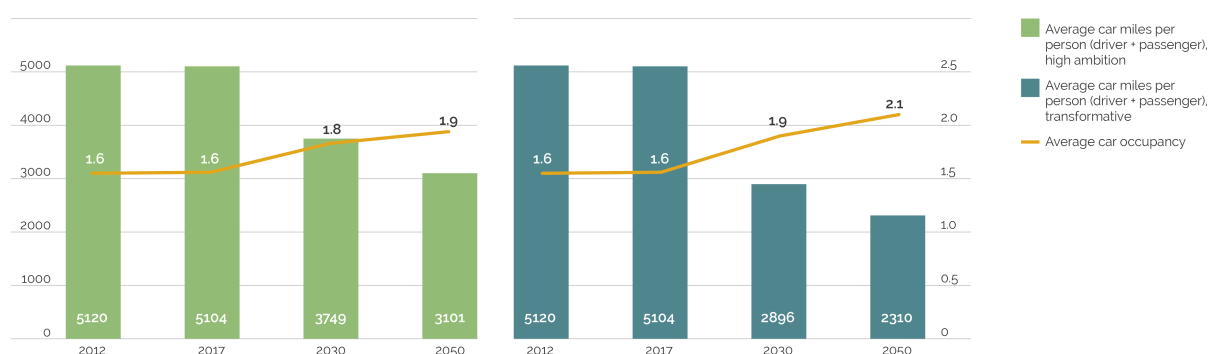
Finally, when looking at cumulative emissions of the period between 2020 and 2050, the low energy demand scenarios had 34% (HA) and 43% (TC) lower emissions totals than the BAU case. In a transformative future (TC), cumulative emissions from domestic transport were 2.4 GtCO<sub>2</sub>-e compared to 4.3 GtCO<sub>2</sub>-e in the BAU case. This large reduction was due to the earlier gains from 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.

## 4.3 Travel demand shifts in a low energy demand future

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

The low energy demand scenarios gave large reductions in distance travelled by car as a driver or a passenger (either in a private or a car club car, taxi, ride share) 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 (HA) and 5,800 (TC) miles per person per year in 2050.

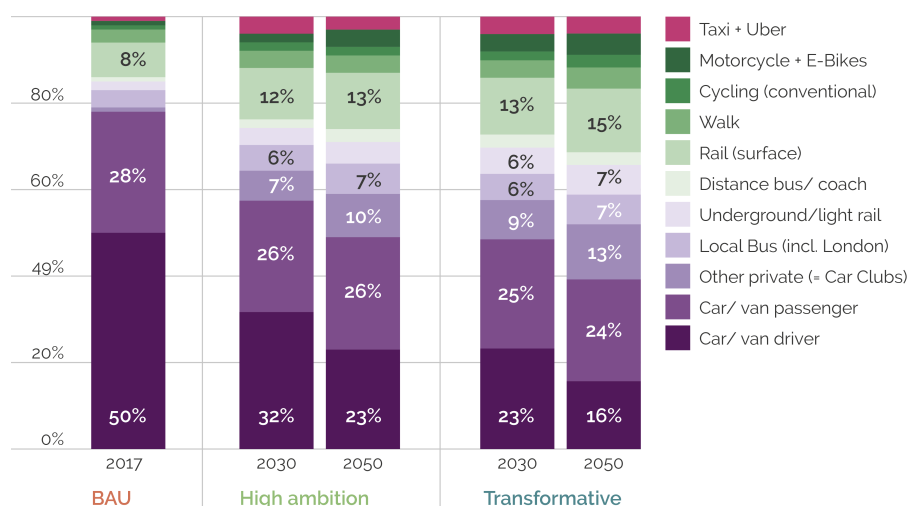
**Figure 4: Change in average per capita car miles + average car occupancy. Left panel: High Ambition, right: Transformative Change**



Notably, 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 (HA) and 2.1 (TC), which was largely due to increases in occupancy for leisure, commuting and school travel (with changes to business travel somewhat limited).

People in the LED UK future scenarios 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 rather than central HQs. By 2030, the car is still used for the majority of distance travelled either as a driver or passenger (either in a private or a car club car), but this drops to 49% (HA) and 40% (TC) of distance travelled per capita by 2050. Using 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 [75-77] and most people's capability [78]. Implicit in the assumptions made here is the fact that private cars are increasingly banned or priced out of urban areas.

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

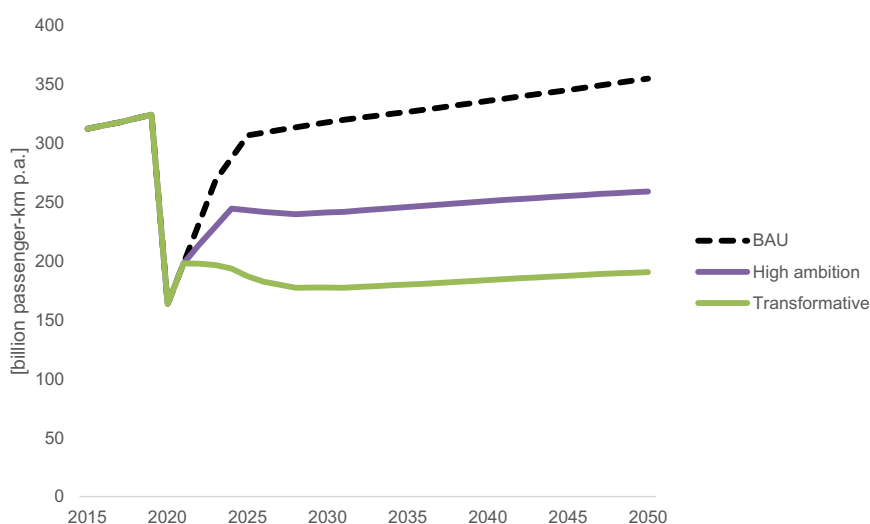


#### 4.3.2 Air travel

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-quality rail (assuming investment in significant new local and long distance rail capacity), 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 the short term effects of the COVID-19 pandemic on business and, less so, leisure air travel, *international* air travel in the LED futures is up to 27% (HA) and 46% (TC) lower in 2050 than in the BAU case (Figure 6). In the medium to long term, these reductions are due to higher costs and prices (to reflect external costs of flying (air pollution, climate change incl. contrails uplift, noise), and social 'unacceptability' of flying longer distances. A new frequent flyer levy and increased air passenger duty reduce trip rates (people fly less but stay longer) thus reducing 'hypermobility' [79] and 'binge flying' [80]. However, without further action on curbing passenger demand and removing fossil fuels from the supply chain [81], air travel is expected to increase resulting in significant residual emission from international air travel by 2050.

**Figure 6: International air travel, scenario comparison**



#### 4.3.3 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

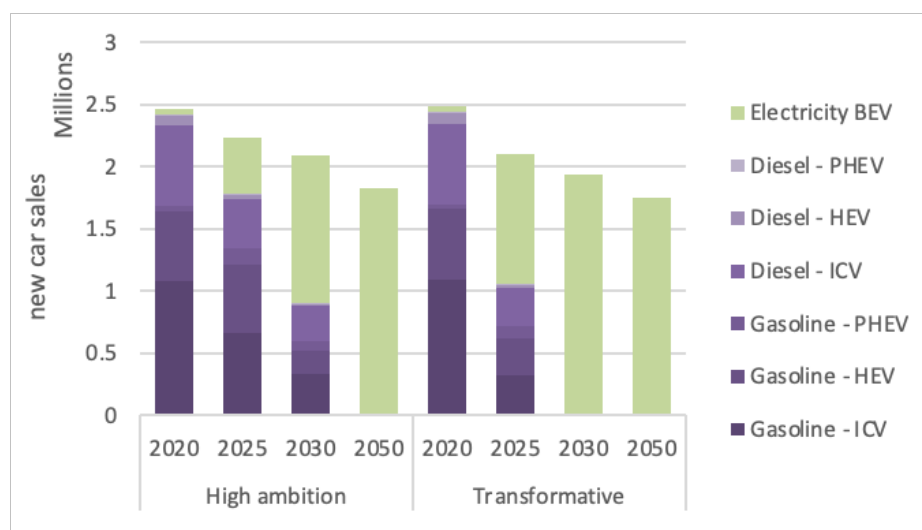
centres increasingly ban heavy goods vehicles but allow electric e-cargo bikes and vans, and local traffic regulations will give priority to professional home delivery, centralised parcel lockers close to the homes, and consolidated urban distribution with clean vehicles. As a result, the overall distance 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.

#### 4.4 A smaller and cleaner vehicle fleet

In our LED futures, 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’ [82]. This is substantially lower than the BAU case, which could see up to 43 million cars on the road by 2050 [21].

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 7) and much improved market availability across many vehicle market segments. While the UK’s Zero Emission Vehicle Mandate [83], announced in October 2023, is met in the TC scenario, motor manufacturers undershoot the mandate by about 16% in the HA case. Take-up by the mass market and so-called ‘user-choosers’ [58] from the mid 2020s mean that BEV take over as the dominant choice of vehicle in this decade, well before the phase out date of 2035 announced in October 2023 [83]. In contrast to the BAU case, total new car sales decrease over time as driving licence uptake is down with transition to ‘car usership’ (Figure 7).

**Figure 7: New car sales by primary fuel and propulsion technology**



#### 4.5 Co-benefits that improve quality of life

##### 4.5.1 Reduced local air pollution for better health

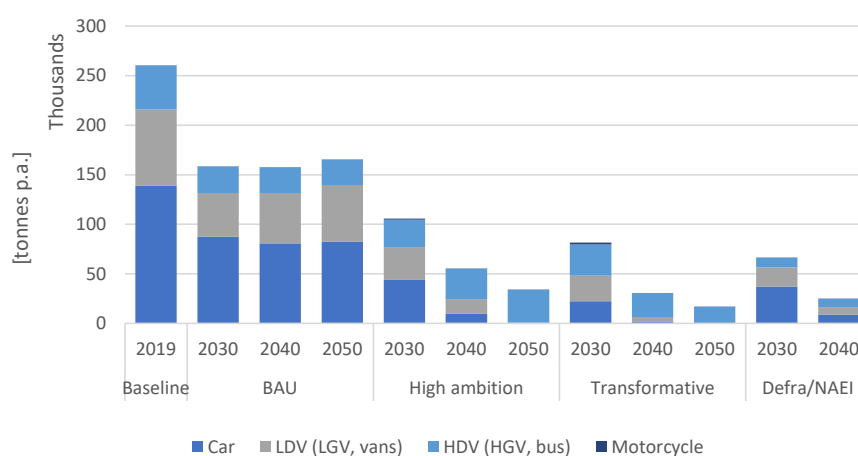
It is likely that the large reductions in air pollution from meeting net zero would make a significant contribution to meeting the UK’s air pollution targets [84]. The health benefits of reduced air pollution are well documented [85]. For example, the Air Quality Life Index 2022 update estimates that 2.2 years would be added to global average life span if the World Health Organization’s stringent targets on particulate matter were met [86].



Air pollution comes from direct emissions (from exhaust or particles from tyres/brakes wearing down) and from indirect emissions (from fuel production and vehicle production, maintenance and disposal). Here we focus on direct emissions from road traffic, which have presented a major public health challenge for some time, particularly fine particulate matter (PM<sub>2.5</sub>) and nitrogen oxides (NO<sub>x</sub>).

Direct NO<sub>x</sub> emissions (Figure 8) show downward trends only for the two LED scenarios, largely due to lower levels of road traffic and plug-in vehicles replacing older, more polluting ones. Even by 2030, direct NO<sub>x</sub> emissions from road transport would be expected to be less than half of those in 2019. In the longer term, direct NO<sub>x</sub> emissions are lowest in the TC scenario due to lower levels of traffic, more shared mobility, more efficient driving and higher rates of vehicle turnover and accelerated switch to BEVs. Without any policy, technological and societal changes (BAU scenario), direct NO<sub>x</sub> drop by about 40% between 2019 and 2030 but then stay flat and even increase, largely due to increased use of vans. Interestingly, neither LED scenario achieves UK Government projections (highlighted by the Defra/NAEI bars in Figure 8) [87], therefore further clean air measures should be considered.

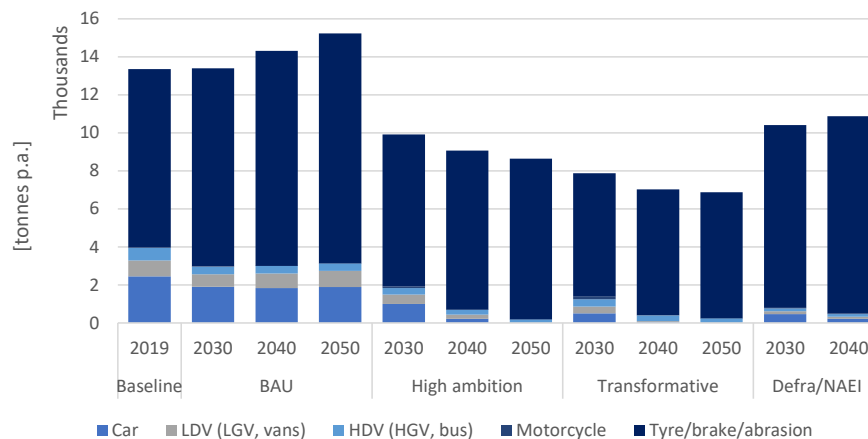
**Figure 8: Direct NO<sub>x</sub> emissions from road transport, tailpipe only**



Notes: Defra=Department for the Environment, Food and Rural Affairs. NAEI=National Atmospheric Emissions Inventory. Defra/NAEI data from [87].

Fine particulate matter (PM<sub>2.5</sub>) stems from both tailpipe and non-tailpipe sources (tyre and brake wear, road abrasion) and is highly toxic to humans [88]. Even today most PM<sub>2.5</sub> from road transport is released from brake, road and tyre abrasion, not from the vehicle tailpipe (Figure 9). Non-exhaust emissions are predicted to be responsible for 90% of all road transport emissions and 10% of all UK primary emissions of PM<sub>2.5</sub> by 2030 [89]. As for future exhaust emissions, the scenarios show accelerated reductions in *tailpipe* PM<sub>2.5</sub> emissions in the short to medium term, and significantly reduce them in the long term. By 2030, *tailpipe* PM<sub>2.5</sub> emissions are 65% lower than the 2019 levels in the TC scenario, driven by larger reductions in private car use that is offset by increases in public transport use. By 2050, *tailpipe* PM<sub>2.5</sub> emissions are virtually eliminated in the LED scenarios, with residual emissions coming from buses and HGVs.

**Figure 9: Direct PM<sub>2.5</sub> emissions from road transport, exhaust and non-exhaust**



Notes: Defra=Department for the Environment, Food and Rural Affairs. NAEI=National Atmospheric Emissions Inventory. Defra/NAEI data from [87].

However, whilst electrification, mode shift and travel demand reduction may help reduce emissions in the future, these can never be fully eliminated [89, 90]. Even with a fully decarbonised vehicle fleet, non-exhaust emissions would continue, particularly from tyre wear and road surface abrasion (Figure 9). Abatement measures are somewhat limited and include (apart from driving less) managing driving patterns towards lower speeds and less braking, on-vehicle brake-wear capture, development of low-wear tyres and road surfaces, and road sweeping/washing and application of dust suppressants to road surfaces. However, there is little evidence that these measures are effective at mitigating non-exhaust PM<sub>2.5</sub> emissions in the long term [89].

Taken together, air pollution and its adverse impact on health would be lower only in the LED scenarios where we have assumed higher rates of technological and societal change where number of (private) vehicles and miles travelled are both reduced. Yet PM<sub>2.5</sub> pollution remains to be a significant challenge.

#### 4.5.2 The health benefits of active travel modes outweigh the potential risks

Overall, the LED scenarios revealed substantial health benefits associated with increased walking, cycling and e-biking, with the health benefits (more physical activity) outweighing the potential risks (increased exposure to air pollution and crash risks) for those who are travelling actively.

As shown in Figure 10, the population's overall physical activity level was projected to increase between 2019 and 2030 as a result of mode shift to active travel, to walking in particular, estimated to *prevent* 2,693 (HA) and 3,788 (TC) premature deaths annually. The prevalence of chronic diseases, including cardiovascular diseases, obesity, and type 2 diabetes, was expected to decline, leading to improved overall population health and well-being. By 2050, the health impact of increased active travel was projected to be even more significant, with an estimated 4,000 (HA) and 4,232 (TC) deaths prevented annually, with walking and e-biking presenting the majority of benefits. Furthermore, the increased exposure to air pollution for users of active travel modes, particularly in areas with heavy traffic congestion or high levels of pollutants, may have adverse health effects. We estimated that between 2019 and 2030, mode shift to active travel *caused* 87 (HA) and 139 (TC) premature deaths annually. By 2050, this increased to 150 (HA) and 161 (TC) premature deaths annually. In addition to physical activity and air pollution, crash risks associated with increased active travel *caused* 354 (HA) and 617 (TC) premature deaths in 2030. By 2050, this increased to 658 (HA) and 735 (TC) premature deaths annually.

The LED scenarios assumed the necessary implementation of high-quality infrastructure, policy measures, and urban planning to reduce air pollution exposure and enhance the safety of pedestrians and cyclists, ensuring that the health benefits of active travel modes continue to outweigh the potential risks.

**Figure 10: Health impact assessment of changes in walking, cycling and e-biking in 2030 and 2050 compared to baseline (2019)**



Notes: HIA analysis using HEAT v5.2 (July 2023) and reporting premature mortality only; PA=physical activity; AP=air pollution exposure; Crashes=crash risk.

## 5 Discussion: what policies and strategies might deliver?

Policy measures and strategies on how and when to implement them play a vital role in driving the wide range of changes in energy demand to deliver on our net-zero goals. However, the feasibility and deliverability of these policy measures are crucial to ensure their successful implementation. In this regard, it is important to identify the primary policy areas and strategies for integrated policy making that have the potential to deliver the necessary changes in energy demand. This section discusses (a) the main policy instruments that might be used to deliver the changes assumed in the LED scenarios and (b) the cumulative necessity and value of multiple policy changes matter to deliver multiple benefits at multiple scales to a range of actors (transport and non-transport).

### 5.1 Avoid-focussed policies

Incentivizing travel demand reduction is a significant challenge that has yet to be fully addressed, with fuel taxation being the only established policy measure in place. Land use planning change can play an important role in reducing the need to travel, for example by supporting urban densification and the provision of local services, e.g. in '15 minute neighbourhoods' [44]. In some cases, there is the opportunity to encourage and build on existing travel-reducing, social trends, e.g. in e-commuting, e-retail, and aiming to 'lock-in' some pandemic driven travel changes [50] and a four-day working week. 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). Many of these changes happen predominantly in urban areas, though the reconfiguration of price signals, renewed emphasis on localisation and normative shifts (e.g. air travel, car usership) are widespread.

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 [91, 92]. 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. emission-based 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.

For aviation, taxation of aircraft movements, distance travelled, and aircraft use are options that can be considered. As mentioned before, there is growing interest in the use of progressive taxation via frequent flyer levies [93]. Research suggests that policy fairness and effectiveness appear to be crucial aspects for the design of such policies [94].

## **5.2 Shift-focussed policies**

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" [95]. 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 (e.g., WHO HEAT could provide monetary valuations of costs and benefits), 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.

In general, especially where public transport provision has been marketised, greater coordination and planning will be needed to move towards more sustainable systems. As the LED scenarios have shown, disinvestment will also be needed in new roads and airport capacity.

## **5.3 Improve-focussed policies**

Light vehicle efficiency improvements have historically been delivered principally by continental-scale product standards, typically applied as manufacturer corporate average, such as Corporate Average Fuel Efficiency (CAFE) standards in the USA [96] and CO<sub>2</sub> Performance Standards (Regulation 2019/631 and its predecessors) in the EU [97]. These can continue to be the main driver of efficiency. Forthcoming requirements for zero-carbon emissions (at the point of use) will principally result in a shift to battery electric vehicles (BEV), which are typically three times more energy efficient than internal combustion engine (ICE) vehicles. The policy framework for net-zero is therefore, itself, a major driver of efficiency improvement. However, it will be important to retain use of efficiency standards for new vehicles, not just before electrification, but also subsequently to ensure adoption of BEVs that are efficient, as inefficient and overly large and heavy BEVs (similar to large SUVs) will drive up electricity use unnecessarily, increasing consumer costs and slowing the speed of electricity sector decarbonisation [54, 98]. Standards for local government, electricity network owners and operators, and private developers will also be important in vehicle charging technology to enable interoperability.

Efficient vehicle technology standards can be supported by national taxation policy [61]. Substantial taxes for liquid road fuels already form an important component of vehicle efficiency policy in many countries. As well as driving efficiency, these raise government revenues, which are therefore threatened by the shift to electricity as the main transport fuel. Differential vehicle taxation can be a useful alternative, at the point of first vehicle registration and/or in use licensing [61]. This can provide incentives to purchase more efficient vehicles, but do not address the other important impact of fuel taxation – the incentive to use private road vehicles. This can be addressed by wider use of taxation proportional to vehicle use (road user charging), which has traditionally been used only to disincentivise car use in major cities (congestion charging) [99, 100].

There is no detectable policy attention 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.

**Table 3: Principal policy instruments for low energy demand mobility**

<b>LED scenario assumptions</b>	<b>Primary Policy Area(s)</b>
<b><i>Transport demand avoidance measures</i></b>	
No more development on greenfield sites	National and local land use planning
Reduced demand for aviation driven by increased public awareness and higher costs	Aviation taxation; fuel taxation; airport policy
Reduced mileage due to destination shifting	Planning for 15-minute cities, localisation
10% reduction in commuting trips per person by 2030 (due to four-day working week and teleworking)	Existing trend; employment legislation
Increased car occupancy from more shared mobility, leading to avoided car trips and reduced congestion	Promoting parking and incentivising ridesharing, car sharing, car club services
Reduced business travel due to greater reliance on video-conferencing	Existing trend; vehicle and fuel taxation
Increased load factors for road freight through improved logistics	Existing trend; vehicle and fuel taxation
<b><i>Modal shift measures</i></b>	
Investment in public transport, walking and cycling	Public investment; transport planning
No more major road or airport infrastructure	Public investment; strategic planning
Increased rail capacity	Public investment
Integrated transport planning in every city and region	Transport governance; land use planning; road use taxation
Freight consolidation centres in cities and major towns.	Investment incentives; transport planning
Increased utilisation of car fleet/ lower car ownership	Vehicle taxation; transport planning
Disincentives for single occupancy car use, household multicar ownership and high use of cars	Vehicle taxation; fuel taxation; transport planning;
Bus and taxi use increased	Vehicle taxation; fuel taxation; transport planning
Increase in light commercial vehicle due to more online shopping	Existing trend; vehicle and fuel taxation; transport planning
<b><i>Improved vehicle efficiency measures</i></b>	
Phase out of ICE, PHEV and HEV cars from 2025	Product standards; vehicle taxation, fuel taxation; road use taxation
Ban large SUVs from sale and use in cities	Product standards; urban access restrictions and/or charging

Buses and taxis all electric by 2030	Product standards; local licensing
New light commercial vehicle all electric from 2030	Product standards; vehicle taxation
Standardised electric vehicle charging infrastructure	Product standards
Accessible electric vehicle charging infrastructure	Public investment; investment incentives; co-ordinated strategies between stakeholders for public infrastructure

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### ***Vehicle manufacturing and use***

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Reduce steel without material or alloy changes	Product standards related to maximum embodied energy per vehicles; EPC extended to full vehicle life
Increase in recycling rates of vehicles	Public investment in EAF; material standards for recycling related to separation
Additional weight saving of car bodies	Product standards related to maximum embodied energy per vehicles; EPC extended to full vehicle life
Steel fabrication yield improvement in cars	Product standards related to maximum embodied energy per vehicles; EPC extended to full vehicle life
Vehicle light-weighting	Variable rates of vehicle taxation based on weight and energy use
Smaller vehicle fleet on the road	Car clubs; VAT reductions; public investment in shared mobility
Using cars for longer	Switch to electric vehicles delayed

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As the LED scenarios have shown, energy demand reductions are further driven by policies that foster conversion efficiency benefits of electrification (electric cars lasting longer for example) and broader changes in societies' use of transport infrastructure and the ability to optimise their use. These go beyond traditional energy efficiency policies and include product standards (e.g. light-weighting, ban on using large SUVs in cities), consumer rights, building regulations and planning as well as the use of public infrastructure investment, the promotion of new service-based business models and tax breaks where appropriate.

The shift to zero tailpipe emission vehicles requires infrastructure investment in both vehicle charging, refuelling and the wider supply system. In the short term, e-charging networks will need to be expanded everywhere but particularly into suburban and rural areas including a substantial programme of residential on-street charging. This calls for place-based targets of charging points based on the projected uptake from our scenarios, relating to availability of off-street parking. In the longer-term similar measures may be needed for hydrogen for heavy duty vehicles. However, existing infrastructure providers may have a vested interest in slowing the transition to zero-carbon, and this could be a potential obstacle to infrastructure investment. Therefore, active policies must be put in place to encourage infrastructure investment in advance of user need.

### **5.4 Revisiting integrated policy making**

The transport sector has never been very good at integrated policy making and coordination with other sectors, e.g. housing. Climate change is a wicked problem and defies simple solutions (hence why the technology silver bullet fails). Even if it is not possible to implement all of the policies we have identified here, then there is still a clear recognition of the elements of the package which have to be bound together.

There is comparatively lower advantage to, say, building high-quality cycle infrastructure and bus lanes if we do not address the falling cost of car use as we go electric. A shift to a more shared and more intensively used fleet would have implications for the charge infrastructure and its use. Land-use changes in response to *Avoid* strategies will impact on servicing strategies. These piecemeal strategies typify much of the policy response we see today but we have to be honest about their potential.

Without clarity over the prize of achieving coordination why would such a task be undertaken? This work shows multiple benefits at multiple scales to a range of actors (transport and non-transport). Outside the sector, a smaller, more multi modal transport system requires less (new) infrastructure and construction materials. More home- and hub-working has implications for housing and domestic vs commercial energy consumption patterns [25]. Crucially, a mixed, coordinated strategy would reduce the very real risk of failing to achieve climate objectives should unproven technologies (such as carbon dioxide removal at scale) or social change (such as social norms of flying) do not materialise in a timely manner.

## 5.5 Limitations of this study

The strength of this work is the development and application of a comprehensive framework for modelling low energy demand scenarios and integrated strategies in the transport sector. However, the approach taken comes with a number of limitations. First, our scenarios heavily depend on a multitude of assumptions, including changes in policies, societal behaviours, political will, technological advancements and economic factors. The plausibility of our model's projections is inherently uncertain, likely resulting in deviations from real-world outcomes particularly in the longer term. We have followed recommendations by Skea et al. [35] and selected the most appropriate methods and realistic, evidence-led assumptions to deliver plausible futures of transport-energy demand at the national level. Second, the scenarios assume significant shifts in societal behaviour and norms. Achieving such changes in practice is a complex challenge, and our study may not fully capture the real-world complexities of changing behaviour, especially at the scale and speed assumed. Third, we base our scenarios on the assumption of widespread adoption of advanced technologies, such as the electrification of the entire car fleet. While we consider potential hurdles, real-world implementation may encounter obstacles not fully accounted for. Fourth, external factors like global economic conditions and unforeseen technological breakthroughs can significantly influence the transport and energy sectors. Our study does not incorporate potential impacts of these external factors. Fifth, we do not extensively address the potential equity implications of our scenarios. The impact on different population groups and regions may vary, and issues related to accessibility, affordability, and social justice require further exploration. Sixth, our scenarios are primarily based on UK-specific conditions, limiting their direct applicability to other regions and cultures. Generalizing the findings to other contexts should be approached with caution. Lastly, achieving the significant shifts in travel behaviour as assumed in the scenarios may be challenging and may not fully align with societal preferences, leading to potential implementation challenges.

In light of these limitations, further research and real-world testing are necessary to validate the feasibility and effectiveness of the proposed scenarios. We maintain that, given the certainty that BAU planning will fall short, it is increasingly necessary to imagine responses and packages of responses beyond that which the current evidence base will suggest is possible or potentially effective and with that comes an acceptance of uncertainty from some of these limitations. It is also necessary, as we have presented here, to present decarbonisation pathways alongside estimates of a broad suite of co-benefits. A vital next step is to design and test communication strategies which would precede and accompany the implementation of the policy packages. The experience of the COVID-19 pandemic has shown that it will be necessary to present science-based assessments of the potential and actual effectiveness of interventions, their wider benefits and disbenefits and the distributional impacts [101].

## 6 Conclusions

The aim of this paper was to investigate the potential contribution of transport energy demand reduction to climate change mitigation and improving public health. Through the utilization of a comprehensive bottom-up modelling framework, we estimated the potential for reducing energy demand associated with mobility at a country level. By employing a structured 'storyline' approach and analysing current travel choices in terms of journey purposes, lengths, and modes, we captured the potential impact of long-term societal changes on travel volume and composition. This analysis incorporated non-price determinants of behaviour (values, norms, fashion, trust, knowledge) and non-consumptive factors (time use, mobility, social networking, policy acceptance).

Our findings indicate that significant reductions in mobility energy demand of up to 61% by 2050, compared to baseline levels, are feasible without compromising citizens' access to jobs, services, and overall quality of life. This translates into substantial lifecycle carbon emissions reductions of up to 72% by 2050, relative to 2020 levels, albeit still not sufficient to meet the UK government's legislated carbon targets. Approximately half of these reductions stem from mode shifting, travel avoidance, and efficient goods movement, while the other half results from vehicle energy efficiency, electrification,

and downsizing of vehicle fleets. These results demonstrate that energy demand reduction in the transport sector can facilitate the achievement of sectoral carbon budgets and mitigate the need for more stringent car use restrictions in the future. Notably, this trade-off was supported by members of recent Climate Assemblies in the UK, who endorsed restrictions on the types of cars driven to establish a modest limit on future car use for all citizens [102].

The significance of mobility energy demand for the global energy system becomes evident. Higher energy demand for mobility necessitates a larger electricity system and hinders the transition to carbon-free energy production as well as driving up costs. Our findings imply that meeting the UK's legally binding carbon budgets by 2030 and 2035 and achieving net-zero emissions by 2050 without substantial energy demand reductions in the transport sector would be unachievable. In the absence of such reductions, GHG emission reductions in the sector would also rely on complete decarbonization of a considerably larger energy supply system and larger vehicle fleets. Given the evidence presented in this paper, it is imperative for the UK Government to develop a detailed strategy and implement supporting policies to enable transport energy demand reduction, playing a crucial role in achieving rapid emissions reductions. Additionally, it may be risky to rely solely on unproven or still-developing technological solutions like power-to-liquid (e-fuels) and sustainable aviation fuels to decarbonize challenging sectors such as long-distance freight and aviation.

Government initiatives have predominantly focused on improving technology efficiency while neglecting other mechanisms that involve reducing the need for mobility. Such an approach is very short sighted. Technological change is always part of behaviour change, as people adapt to the costs or performance differences of the new product (e.g. EVs). We demonstrate the need for behaviour change which ensures we avoid the already foreseeable downsides of business as usual.

These scenarios demonstrate the feasibility of reducing the UK's transport energy demand by more than half. To achieve the necessary extent and speed of energy demand reduction, both accelerated energy efficiency improvements and shifts in travel patterns to minimize energy consumption are required. Importantly, our low energy demand scenarios do not compromise quality of life; instead, they aim to enhance it by promoting active living, clean air, safe communities, work-life balance, and reduced inequality.

The deliverability of these policy measures requires a comprehensive and coordinated approach, something which has proven elusive in transport for many decades, despite its figurative appeal. Whilst there are multiple benefits to be attained from such a shift, a word of caution is warranted as we are still some distance away from envisioning and realizing these futures. The window of opportunity for such transformative changes is not open indefinitely. If we prioritize rapid electrification while failing to address other forms of energy demand and the wider costs of mobility, lower energy futures will become constrained as people become locked into low-cost e-mobility. The easier political choice is Business as Usual which will deliver worse outcomes across the board. We conclude that there is both the potential and the agency to switch to a path of healthier, fairer, and fulfilling lower energy demand mobility futures. Whether this is grasped will be a major component of how close we can hold to prospects of warming of 1.5C.

## **CRediT authorship contribution statement**

Christian Brand: Writing - original draft, review & editing, Conceptualization, Methodology, Software, Formal analysis, Funding acquisition, Investigation, Data curation, Visualization. Greg Marsden: Conceptualization, Methodology, Investigation, Funding acquisition, Writing - review & editing. Jillian Anable: Conceptualization, Methodology, Investigation, Funding acquisition, Writing - review & editing. James Dixon: Methodology, Investigation, Writing - review & editing. John Barrett: Conceptualization, Methodology, Funding acquisition, Writing - review & editing.

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## **Appendix A. Supplementary data**

Supplementary Material



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