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Achieving deep transport energy demand reductions in the United Kingdom

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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 people's physical and mental health. This research investigated the potential contribution of transport energy demand reduction to climate change mitigation and improving public health. Using a comprehensive bottom-up modelling framework, the Transport Energy and Air pollution Model (TEAM), this study provides an integrated assessment of the impacts of deep mobility-related energy demand reductions, including lifecycle carbon emissions, local air pollution and health impacts. Using a sociotechnical scenario approach and the UK as a case study, this research 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, 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. The research shows that it can lead to significant co-benefits such as improved local air pollution and public health. The feasibility and practicality of policy measures and integrated strategies identified for achieving deep transport-energy demand reductions are discussed.

1. Introduction

As economies and populations grow, demand for goods grows, as does the number of people with the desire and means to travel. Under baseline assumptions, total global transport activity is expected to more than double from 2015 to 2050, resulting in a 60 % increase in transport carbon dioxide (CO_2) 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.

There is a growing consensus in advanced and developed economies that net zero (NZ) compliant pathways in transport sector emissions may require the transformation of the whole transport system [1,3–5]. Research has shown that this transformation may involve a combination of measures such as fuel efficiency improvements, fuel switching, modal shifts, including a shift away from car-dependent lifestyles [6], supported by the development of more compact and mixed-use urban environments that offer a range of services and amenities within walking or cycling distance [7] and the integration of land use and transport policies that prioritize walking, cycling, and public transport as the backbone of urban transport [8]. Transitioning from oil to low-carbon energy vectors, such as low-carbon electricity, can significantly cut emissions by 2050. Electric vehicles are about three times more energy efficient than their conventional internal combustion engine counterparts. However, even in an optimistic scenario where 60 % of global new car sales are electric by the end of the current decade, CO_2 emissions from cars would decrease by only 14 % by 2030 compared to 2018 [9]. One reason is that even if all new cars were electric starting today, it

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Abbreviations

BAU	Business-as-usual, scenario name
CAFE	Corporate Average Fuel Efficiency (USA)
CO_2	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

would take 15–20 years to replace the world's fossil fuel car fleet [10]. Another reason is that larger, heavier and often more powerful electric vehicles not only require more resources to build – thereby increasing their environmental footprint – but also undermine the potential gains from electrification due to their greater energy consumption and associated emissions across the vehicle and fuel lifecycles [11]. Some measures, such as fossil fuel taxes and zero-emission vehicle incentives, can be implemented quickly, while others, such as international agreements on fuel taxes and route optimization, require longer-term cooperation. Measures like road-space reallocation [12] and higher fossil fuel taxes for road use [13] face resistance, necessitating a sequence of complementary policies for a fair 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 [14–17]. Technological advances alone are now understood not to be capable of delivering emissions reductions fast enough to meet the mitigation goals implied by the Paris Agreement [1,18]. Global efforts such as the UN Climate Change Conference of the Parties (COP) have focused entirely on road-transport electrification [19]. While the transition to electric or hydrogen (H_2) vehicles would allow the sector to decarbonize at the tailpipe (or direct, at source), life-cycle emissions from electric or H_2 vehicles are significant and greatly depend on the carbon content of electricity, primary fuel (e.g., natural gas or solar electricity for H_2 production), battery or hydrogen storage technology, and materials used [20]. Any holistic analysis on the benefits of shifting to electric or H_2 needs to consider increased generation, transmission and storage capacity, posing strains on power networks and grid overloading risks unless appropriately planned and invested in Refs. [21–23]. Furthermore, the challenges extend beyond cars and light goods vehicles (vans), as air travel and heavy goods transport may only be partially electrified over the time horizon of this study [24,25]. Using 'green' (i.e. from renewable not fossil energy sources) H_2 for transport has significant potential but continues to be limited by issues of lower energy density (limited storage in light duty vehicles) and significant GHG emissions during the production phase [20]. When looking beyond transport to other sectors transitioning to electricity, such as domestic heat [26], the combined demand for additional electricity could necessitate an electricity system four times larger than the current one [2].

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 (ASI) hierarchy [27–29] of avoiding travel (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). The ASI hierarchy has been used extensively in the past, including in the framing and analysis of *Demand, Services and Social Aspects of Mitigation* (Chapter 5) in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [30], the role of demand-side mitigation strategies in Germany [31] policy mixes for sustainable mobility [32] and as an opportunity for transport decarbonisation after the Covid-19 pandemic [33].

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 [34]. 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 [35], especially in the developing world where electric cars may well only be an option for the powerful and wealthy, and electric motorcycles, three-wheeled vehicles, and inexpensive small electric cars may be more competitive and taken up at scale. On the other hand, electric cars could potentially be an important part of making the grid more robust if vehicle-to-grid could become more economical and taken up at scale [36]. Traffic remains the largest contributor to both poor air quality and associated mortality in Europe [37]. While air quality and climate emissions may improve, cheaper electric motoring could introduce new challenges such as increased rates of traffic growth [38]. For example, one study found a 76 % rebound effect of the energy savings EVs can bring [39]. Previous studies that examine the wider impacts and co-benefits [40] of mobility-related energy demand reductions are scarce [41]; this study aims to partially fill this gap.

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 %) [42]. 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 [42]. 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 [43]. It is by far the largest emitting sector (34 % of total GHG emissions, followed by energy supply at 19 % and business).

The primary focus of UK policy has been to change the vehicle fleet from petrol and diesel, first to Ultra Low Emission Vehicles (ULEVs, defined as vehicles emitting less than 75 gCO_2 per km), and then to zero (tailpipe) emission vehicles (ZEVs), 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_2 between 2016 and 2019 [44]. 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 [9]. Electric vehicles (EVs) accounted for 23 % of sales in 2022 [44] (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 [45]. 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 cycle, which is not directly comparable) suggest a 29 % reduction in tailpipe CO_2 between 2000 and 2019 [44]. 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 [46].

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 [35]. A whole of government analysis of the likely pathway from current and planned policies (such as the zero emission vehicle mandate, or ZEVM) which allow for such growth coupled with electrification tracks some 224 $MtCO_2$-e above the pathway set out in the agreed 6th carbon budget [47,48]. 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 $MtCO_2$-e [43]. Crucially, a recent gap analysis for the UK has shown that there is no "technology replacement pathway" still open; and this is now in government documents [49]. Business as usual planning continues in the face of clear and consistent evidence that BAU will fail in climate policy terms as well as in congestion terms [18,38].

This research addresses the central question: what is the contribution that energy demand reduction in transport can make to improve direct and lifecycle carbon emissions, local air pollution and public 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 assessing the wider impacts and policy implications of the changes required.

Using a comprehensive national bottom-up modelling framework, the Transport Energy and Air pollution Model (TEAM), this research provides an integrated assessment of the benefits of deep mobility-related energy demand reductions, including lifecycle carbon emissions, local air pollution and health impacts. Deploying the UK as a case study, the research contributes to the debate and previous findings that reaching the short to medium carbon targets would be impossible without significant reductions in energy demand for mobility [see e.g. [1,18,50–52]].

The paper proceeds as follows. Section 2 describes the scenario and modelling approach adopted to construct the LED scenarios, including the development of the LED narratives and how these were translated into integrated, balanced modelling pathways. Section 3 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. Sections 3 then identifies and assesses what policies and strategies might deliver the pathways before Section 4 concludes with a summary and the main contributions of this research.

2. Materials and methods

This section outlines the scenario and modelling approach that was adopted to construct three contrasting low energy demand (LED) scenarios. The first section outlines the creation of scenario narratives and subsequent development into coherent, plausible scenarios for transport and mobility. The second section describes the use of TEAM in modelling transport energy demand for the BAU and two alternative, low energy demand scenarios.

2.1. Scenario building using coherent storylines

The approach of this study was to develop sociotechnical scenarios, which are detailed, narrative-based projections and system models of how future sociotechnical systems might evolve. Here, scenarios were used as strategic, policy and planning tools for exploring different possible low energy demand 'futures' by combining social, technological and environmental factors. This builds on the existing scenario literature that includes scenarios on how energy demand could be reduced through changes to how society consumes energy services, including mechanisms for change such as 'lifestyle change' [53,54], 'behaviour change' [2,55] or 'social change' [56]. In comparison to other approaches such as sociotechnical imaginaries [57], scenarios tend to be more specific and practical, designed to explore and anticipate the potential outcomes of different decisions (e.g. new vehicle technology choice by households or fleet managers), trends (e.g. ageing of the population, the future of work) and interventions (e.g. fiscal incentives for zero emission vehicles, or investment in public transport infrastructure, vehicles and prioritisation) [58,59].

The 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 [60]. 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.

The adopted scenario approach attempted to give insights into the plausible scale of change in energy demand, carbon emissions, local air pollution (focusing on ultra-fine particulate matter, $PM_{2.5}$ and nitrogen oxides, NO_X) and public health (physical activity, air pollution exposure, crash risks) under certain circumstances and social and technological uncertainties. Three scenarios were created (the LED scenarios from hereon), namely.

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 [27–29] has been used to emphasise the priority ordering and layering of the scenario storylines that stand apart from the dominant supply and vehicle technology-oriented approach to energy demand reduction and decarbonisation in the sector [61]. In essence, the HA narrative envisions a gradual whereas the TC storyline assumes a rapid (TC) change in travel patterns, mode choice, occupancy levels and technological change, leading to relatively fast transformations and new demand trajectories, particularly in the second half of the 2020s. The high-level descriptions and differences of the LED scenarios when compared to the BAU are provided next. The Supplementary Information SI1 provides detailed descriptions and underlying assumptions. First, as strategies to avoid travel demand and car ownership, the LED scenarios considered ways to 'lock-in' demand changes, some of which started well before the COVID-19 pandemic [62], new regulatory frameworks to steer emergent transport innovations, the promotion of 'car clubs' [63] and freight consolidation centres [64], 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 this research 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 demand changes due to COVID-19 have shown that travel avoidance can happen fast, further and more flexibly now [62,65]. 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' [66].

To avoid 'induced travel' from emerging innovations [67,68] such as mobility as a service (MaaS), connected and autonomous vehicles (CAV) and artificial intelligence (AI), this study assumed 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 [68], 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.

Second, as strategies to shift travel to the most sustainable modes, this research 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.

Third, as strategies to improve the efficiencies of individual modes, this work considered 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_2 savings to achieve NZ requires phasing out all forms of conventionally fuelled internal combustion engine (ICE) and hybrid electric vehicle (HEV) cars and vans by 2030 [51,69].

While a comprehensive and sustained eco-driving programme (as in the Netherlands) is part of the HA and TC scenarios, a focus on efficiency of vehicles in use is more than that. It considers maximizing assets in ways that substantially reduces single car occupancy and individual ownership.

The scenario descriptions and key assumptions are provided in more detail in the Supplementary Information SI1.

2.2. Modelling low energy demand scenarios

2.2.1. 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 TEAM modelling framework has been applied in a number of prospective scenario [53,69–72] and policy [73] modelling studies.

A detailed description of the modelling methods is provided in Brand et al. [74], and a description and application of disaggregate vehicle fleet modelling and uptake of electric vehicles in a heterogeneous car market using a consumer segmentation approach was published in Ref. [75]. In sum, TEAM is a strategic, deterministic transport-energy-environment systems model that deploys simulation and predictive modelling methods, with linear (e.g. domestic passenger transport demand simulation model, elasticity based demand model for road freight) and non-linear (e.g. discrete choice modelling, household car ownership modelling, speed-emission curves for energy and emissions) formulation. It covers passenger and freight demand and supply across road, rail, air and shipping. It was built on a SQL database platform and includes hundreds of lines of code, queries and tables.

First, 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 [76], 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 and endogenously as a function of economic activity (GDP/capita), population and supply and policy costs. Freight demand is modelled endogenously as a function of economic activity, population and freight transport prices, with reference demand elasticities taken from Dunkerley et al. [77]. 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. In TC, for example, the road freight demand elasticity with regards to income was assumed to decrease from 0.8 in 2020 to 0.5 in 2030 and further to 0.2 in 2050 [78].

The vehicle fleet turnover model provides projections of how vehicle technologies evolve over time for 1246 vehicle technology categories, including 283 car and 566 van (light commercial vehicles up to 3.5t gross vehicle weight, e.g. panel and side vans) technologies such as increasingly efficient gasoline internal combustion vehicles (ICV), battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and hydrogen (H_2) fuel cell electric vehicles (FCEV). The car and van fleet models are the most detailed, including market (private vs. fleet/company, three car sizes/segments, six van types) and consumer segmentation (four private and two fleet/company segments for cars, two segments for vans). The heavy goods vehicle (HGV) model is somewhat simpler and includes diesel ICV, diesel P/HEV, BEV and hydrogen FCEV drivetrains – power-to-liquid (e-fuels) and overhead catenaries for BEV or PHEV only play a minor role given limited appetite in the UK market to develop and invest in these technologies [79]. New vehicle choice is modelled endogenously using a hybrid discrete choice and consumer segmentation model, as described in Brand et al. [74,75]. Vehicle scrappage probabilities 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

74 for methods]. Note the UK car fleet age profile implied a 50 % scrappage probability applied for cars that were approx. 16 years old. Total car ownership is modelled endogenously based on established methods [80,81] taking into account 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). Technology turnover of rail, shipping and aviation was modelled in TEAM using a simplified discrete choice model (based on costs, performance and market availability), including short, medium and long haul aircraft powered by Jet-A/kerosene (incumbent), electric, bio (blends) and hydrogen fuels.

2.2.2. Energy use and emissions

Direct energy use and air pollutant emissions (in tonnes of CO_2, NO_X, $PM_{2.5}$, CH_4, 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 [82] and supplemented with data from COPERT IV [83] and the UK National Atmospheric Emission Inventory (NAEI) [84]. Non-exhaust emission factors for $PM_{2.5}$ 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 Ref. [74]. This included upstream and downstream emissions from the vehicle and fuel lifecycles. Emissions from electricity generation and transmission were based on central UK government forecasts of energy consumption and emissions [43].

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). This study assessed direct emissions from road traffic, which have presented a major public health challenge for some time, particularly fine particulate matter ($PM_{2.5}$) and nitrogen oxides (NO_X).

2.2.3. 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. [85] and Götschi et al. [86].

2.3. Turning scenario narratives into system modelling assumptions

Starting with the storylines, the LED scenarios were quantified 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. The levers and factors were identified, specified and reviewed by the research team in consultation with academic and policy experts in the UK. This process involved two workshops, each comprising eight experts drawn from the research team, the Centre for Research into Energy Demand Solutions (CREDS), the UK Energy Research Centre (UKERC), and two advisory experts. The experts were engaged through a series of structured discussions, scenario evaluations and small-group deliberations on plausible values for the key factors that quantified the LED scenarios, ensuring that their insights were systematically integrated into the study.

Since providing more than 30 levers (e.g. uptake of teleworking) and over 100 factors (e.g. mode shift from car as diver to national rail for trip lengths of 25–50 miles) would be too long for the main text, two exemplars for each of these strategic areas are given in Table 1: 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 – this work 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 %. For mode shift, this study assumed different substitution rates varying by trip lengths and modes of travel, for example in the 2–5 mile (3.2–8 km) range this study simulated 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 the modelling assumptions are given in the Supplementary Information SI1.

2.4. Assessment of plausibility and feasibility of the LED scenarios

In a final step, this research assessed the plausibility and feasibility of policy and social change to achieve the mobility-related energy demand reductions of the LED scenarios. 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 the UK's NZ goals. However, the feasibility (e.g. political feasibility, governmental capacity, economic viability, social acceptability) and practicality (e.g. coordination across sectors and defined stakeholder groups; timing and phasing) 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 plausibly deliver the necessary changes in energy demand. Building on the developed narratives, assumptions and modelling results, this research identified and assessed (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 that matter to deliver multiple benefits at multiple scales to a range of actors (transport and non-transport).

3. Results and discussion

3.1. 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), as shown in Fig. 1. Fig. 2 shows that the combined effects of 'avoiding' and 'shifting' demand provided more than half of this reduction, particularly early on, with the other half coming from 'improving' demand through electrification, eco-driving, speed limits and improved vehicle occupancy rates and freight load factors. In the LED scenarios early gains were made in the 2020s so that energy demand was 27 % (HA) and 43 % (TC) lower than BAU as early as 2030.

Demand for conventional fossil fuels (gasoline, diesel) was up to 50 % lower by 2030, and up to 80 % lower by 2050, while demand for

Table 1
Selection of six key modelling assumptions for the LED scenarios.

Avoid		Baseline level	High Ambition		Transformative	
Lever & factor	Rationale and supporting evidence	2019	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 [87]. 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 [88] and greater focus on 'quality of life' [89]. No new developments on greenfield sites (to reduce urban sprawl).	144 trips pppa on average	−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.	324 billion passenger-km in total	−23 %	−17 %	−43 %	−39 %
Shift						
3. Mode shift from private car to other modes. *NB: Varies by trip length and mode of travel* (*), e.g. *5 % shift from 'car as driver' to 'local bus' in the 2–5 miles trip length band in 2030*	Significant 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. (*) *varies by trip length and travel mode*	Private car: 8102 PKM per person per year on average	1–20 % shift to other modes each (*) → 5951 pkm pppa	2–25 % shift to other modes each (*) → 4923 pkm pppa	2–25 % shift to other modes each (*) → 4597 pkm pppa	4–30 % shift to other modes each (*) → 3666 pkm pppa
4. Freight: from van (LCV) to micromobility, and from long distance road (HGV) to rail	National freight demand remains disappointingly inelastic. Limited load capacity of e-cargo bikes sees almost exclusive use in urban areas. Assumed large investments in logistics and ICT and renewed push for consolidation centres around big cities and towns to maximize the use of brownfield sites for HGV.	Vans: 24.5 billion tonne-km HGV: 157 billion tonne-km	−2% −1%	−5% −3%	−3% −2%	−7% −5%
Improve						
5. Decarbonisation of vehicle fleets: share of BEV miles in *total* car and van traffic	Sale of internal combustion engine PHEV and HEV motorcycles, cars, buses, vans and HGV are phased out by 2030 (HA) and 2025 (TC) and replaced with a largely electric (with some H_2 fuel cell) fleet. Fleet evolution modelled endogenously.	Cars: 0.5 % Vans: 0.8 %	21 % 11 %	99 % 99 %	38 % 26 %	100 % 100 %
6. On-road fuel efficiency programmes, reduction in energy use per km travelled (by driving more efficiently, technology improvements are accounted for separately)	Speed limits for cars, vans and motorcycles on motorways are lowered (to 100 kph in TC) and enforced effectively. National eco-driving programme for new (HA) and existing (TC) drivers. Speed/acceleration limiters become mandatory for HGV, improved & mandatory aerodynamics.	Cars: 6.0 L/100 km, 16.7 (ICE) kWh/100 km (BEV) Vans: 7.5 L/100 km, 33.8 (ICE) kWh/100 km (BEV)	−3% −5%	−6% −10 %	−8% −10 %	−10 % −15 %

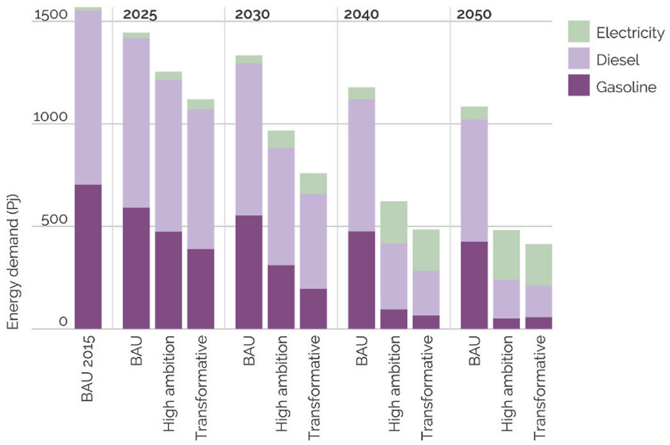

Fig. 1. Scenario comparison of energy demand (in Peta-Joule) by transport mode and fuel – road and rail only. Note energy vectors that contribute less than 2 % of the share (e.g. H_2) have been excluded from this chart.

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 considerable, transport in the LED scenarios is still at least 50 % fuelled by fossil fuels in 2050, resulting in sizeable residual emissions.

3.2. Lowering transport energy demand makes increased climate ambition possible

The low energy demand scenarios resulted in deep reductions in direct (i.e., tailpipe, at source) carbon emissions from transport. Direct CO_2 emissions were up to 54 % (2030, transformative) and 80 % (2050, transformative) lower than in 2020, as shown in Fig. 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 NZ targets easier, with fewer, albeit still significant, changes required to the transport or energy system. Residual emissions in 2050 are largely from road freight, where decarbonisation options may take longer to take effect or do not cover every locality, industry or

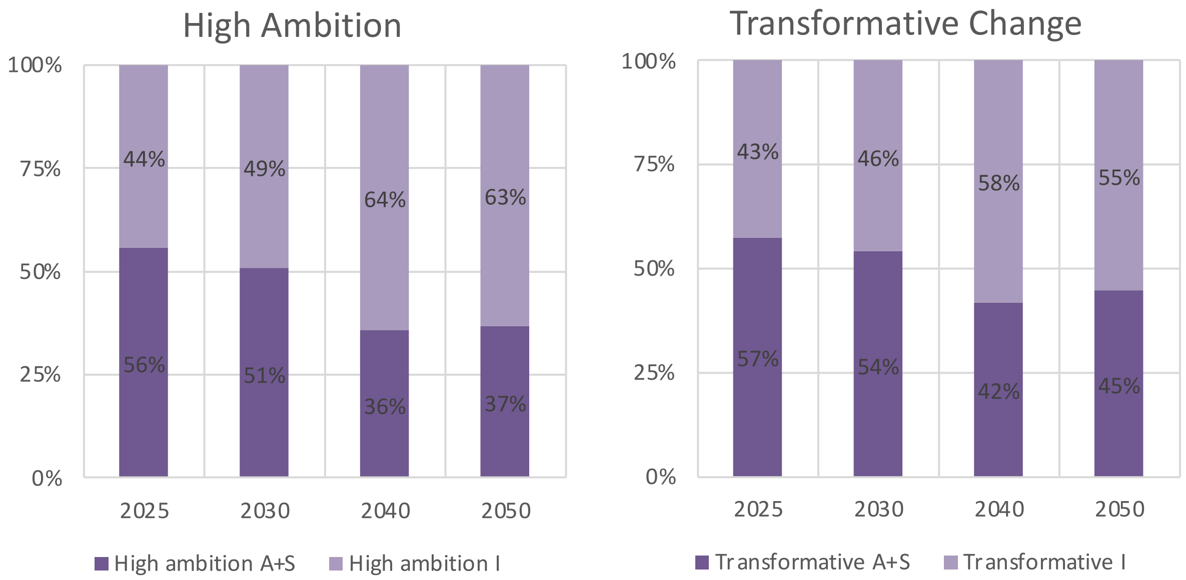

Fig. 2. Contributions of Avoid + Shift (A + S) and Improve (I) components to transport energy reduction (road and rail only). Left panel: High Ambition scenario, Right panel: Transformative Change scenario.

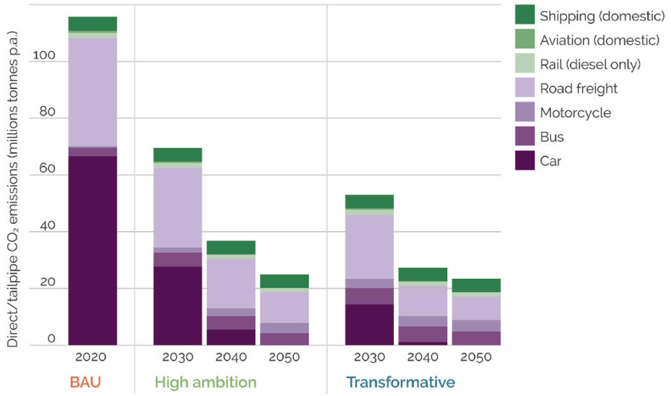

Fig. 3. Scenario comparison of direct CO_2 emissions (domestic transport, excluding international aviation/shipping).

user group (e.g. expect rural buses to be HEV into the 2040s, and there may remain a significant fleet of long haul HGV that are diesel powered in all scenarios).

The TEAM framework allowed us to further assess lifecycle CO_2-eq emissions, which include the above direct emissions as well as indirect emissions from power generation and fuel production, as well as vehicle manufacture, maintenance and disposal [for methods and data, see 74]. 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. Cumulative carbon emissions from domestic transport were 2.4 $GtCO_2$-e in TC when compared to 4.3 $GtCO_2$-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.

3.3. *Travel demand shifts*

3.3.1. *'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, as shown in Fig. 4. This was on the back of only small changes to total distance travelled per person, from about 6600 miles a year in 2017 to about 6300 (HA) and 5800 (TC) miles per person per year in 2050.

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).

Fig. 5 shows that people in the LED scenarios become progressively more 'multi-modal' and less car dependent, particularly in urban areas. 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 removed 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 [90–92] and most people's capability [93]. Implicit in the assumptions made here is the fact that private cars are increasingly banned or priced out of urban areas.

3.3.2. *Air travel*

With regards to domestic air travel, growth in flights saturated and then declined due to growing unacceptability of flying short distances

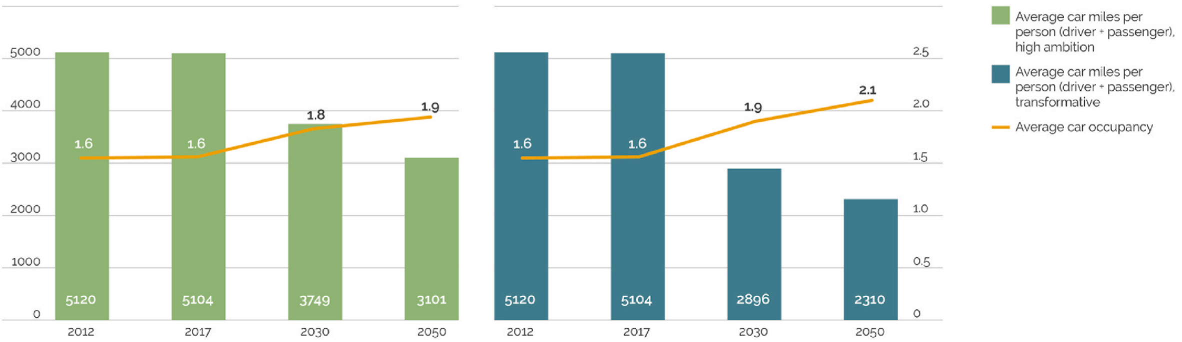

Fig. 4. Change in average per capita car miles +average car occupancy. Left panel: High Ambition, right: Transformative Change.

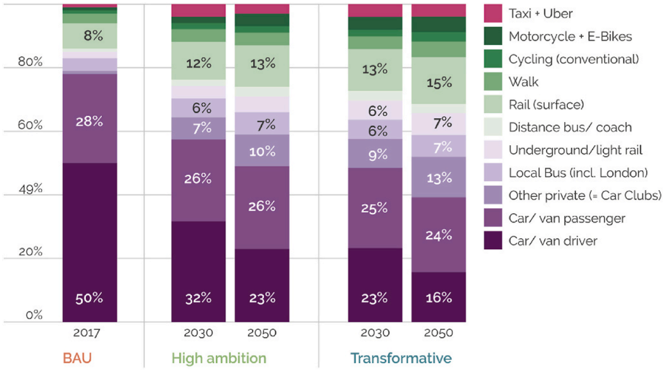

Fig. 5. Change in trip mode shares (by trip distance) across all trip purposes.

(modelled endogenously by lowering future demand elasticities for air travel) and increased prices leading to increasing use of high-quality rail (assuming investment in significant new local and long distance rail capacity) and express coaches (simulated by assuming modest mode shift from air to coach and rail). 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 scenarios is up to 27 % (HA) and 46 % (TC) lower in 2050 than in the BAU case, as shown in Fig. 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’ [94] and ‘binge flying’ [95]. However, without further action on curbing passenger demand and removing fossil fuels from the supply chain [96], air travel is expected to increase resulting in significant residual emission from international air travel by 2050.

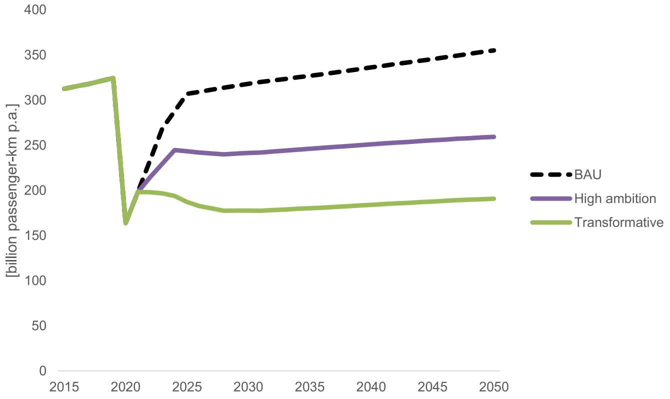

Fig. 6. International air travel, scenario comparison.

3.3.3. *Freight transport*

Due to the continued transition towards a service economy and more teleshopping in the low energy demand scenarios, van ownership and use was projected to increase more than they did in the decade prior to 2020. This shift is a structural trend that was assumed to continue and be more prominent in one scenario over another (an exogenous assumption). 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 significantly less than the 69 % increase depicted in the BAU case. HGV are still set to grow due to economic and population growth. However, mainly as a result of increased load factors (from an average of 50 % in 2020 to approx. 60 % in 2035) 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.

3.4. *A smaller and cleaner private vehicle fleet*

In the LED scenarios, the UK car fleet is expected to plateau in the 2020s and gradually, albeit slowly, reduce in size from the current 31 million to about 23–25 million in 2050, mainly due to a decrease in driving licence uptake, limits on multi-car ownership and a transition to ‘car usership’ [97]. This is substantially lower than the BAU case, which could see up to 43 million cars on the road by 2050 [35].

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. Whilst EVs will be widely available in all vehicle segments and by all major brands by 2030, the market availability of H_2 fuel cell cars and vans is limited. Consumers increasingly accept EVs as the preferred choice over conventional ICV. In a LED world, large cars such as SUVs are phased out from sale by the mid 2020s. Nevertheless, as shown in Fig. 7, 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 and much improved market availability across many vehicle market

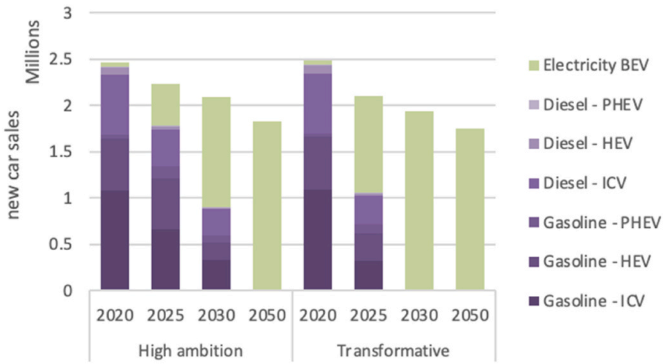

Fig. 7. New car sales by primary fuel and propulsion technology.

segments. While the UK's Zero Emission Vehicle Mandate [98], 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' [75] 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 [98]. In contrast to the BAU case, total new car sales decrease over time as driving licence uptake is down with transition to 'car usership', as shown in Fig. 7.

3.5. Co-benefits that improve quality of life

3.5.1. Reduced local air pollution for better health

Direct NO_X emissions followed 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_X emissions from road transport would be expected to be less than half of those in 2019. In the longer term, direct NO_X 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_X 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 ('central, with policy') [99], therefore further clean air measures should be considered.

Fine particulate matter ($PM_{2.5}$) stems from both tailpipe and non-tailpipe sources (tyre and brake wear, road abrasion) and is highly toxic to humans [100]. Even today most $PM_{2.5}$ from road transport is released from brake, road and tyre abrasion, not from the vehicle tailpipe, as shown in Fig. 9. Non-exhaust emissions are predicted to be responsible for 90 % of all road transport emissions and 10 % of all UK primary emissions of PM2.5 by 2030 [101]. As for future exhaust emissions, the scenarios show accelerated reductions in *tailpipe* $PM_{2.5}$ emissions in the short to medium term, and significantly reduce them in the long term. By 2030, *tailpipe* $PM_{2.5}$ 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* $PM_{2.5}$ emissions are virtually eliminated in the LED scenarios, with residual emissions coming from buses and HGVs.

However, whilst electrification, mode shift and travel demand reduction may help reduce emissions in the future, these may never be fully eliminated [101,102]. Fig. 8 and 9 shows that even with a fully decarbonised vehicle fleet, non-exhaust emissions would continue, particularly from tyre wear and road surface abrasion. 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

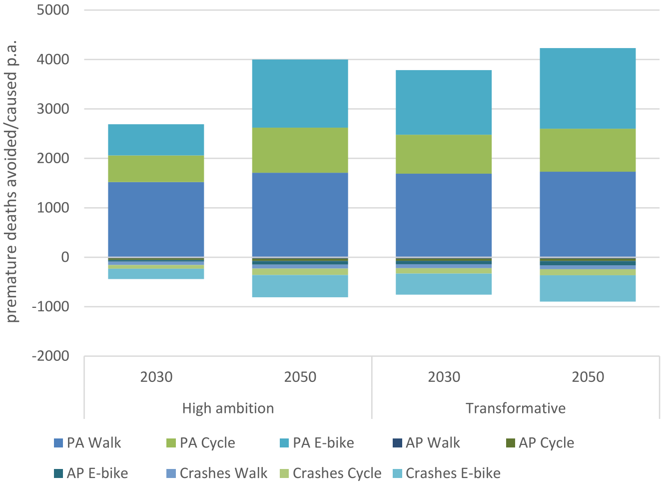

Fig. 9. Health impact assessment of changes in walking, cycling and e-biking in 2030 and 2050 compared to baseline (2019). Notes: HIA analysis using HEAT v5.2 (July 2023) and reporting premature mortality only; PA = physical activity; AP = air pollution exposure; Crashes = crash risk.

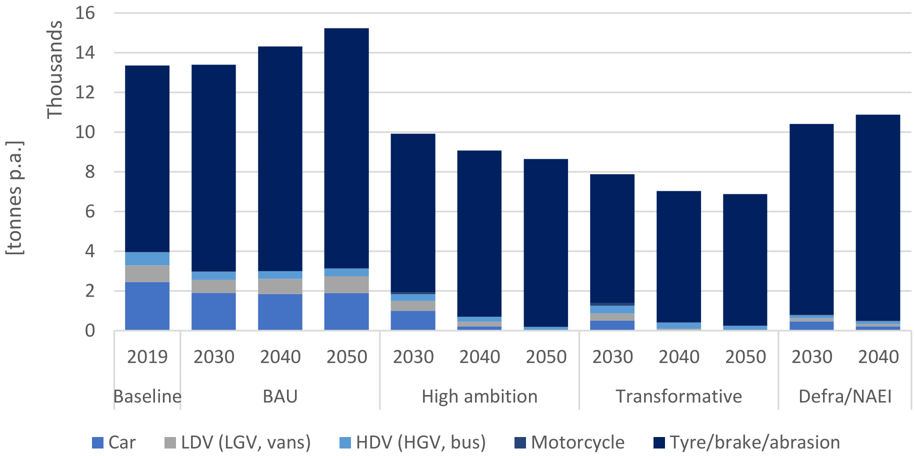

Fig. 8. Direct $PM_{2.5}$ emissions from road transport, exhaust and non-exhaust. Notes: LDV = light duty vehicles (light goods vehicles, vans); HDV = heavy goods vehicles, trucks). Defra = Department for the Environment, Food and Rural Affairs. NAEI=National Atmospheric Emissions Inventory. Defra/NAEI data from Ref. [99].

measures are effective at mitigating non-exhaust $PM_{2.5}$ emissions in the long term [101].

Taken together, air pollution and its adverse impact on health would be lower only in the LED scenarios where higher rates of technological and societal change were assumed and where the number of (private) vehicles and miles travelled were both reduced. However, pollution of ultrafine particulate matter ($PM_{2.5}$) remained to be a significant challenge over the modelling horizon.

3.5.2. 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 Fig. 9, 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* 2693 (HA) and 3788 (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 4000 (HA) and 4232 (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. This study 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 for all and enhance the safety of pedestrians and cyclists, ensuring that the health benefits of active travel modes continue to outweigh the potential risks.

3.6. What policies and strategies might deliver low energy demand scenarios?

This section identifies the main policy instruments and 'policy mixes' that might be used to deliver the changes assumed in the LED scenarios. It further assesses the cumulative necessity and value of multiple policy changes that matter to deliver multiple benefits at multiple scales. The findings are meant to apply to the UK and other jurisdictions.

3.6.1. 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 min neighbourhoods' [7]. 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 [65] 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 [103,104]. 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 while taking parking away from private use, 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 subsidized or free public transport is 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.

Mechanisms like fuel taxation, urban densification, and promoting '15-min neighbourhoods' may disproportionately benefit wealthier urban populations with good accessibility to local amenities and quality public transport. Conversely, poorer rural populations might face higher costs and reduced accessibility, worsening existing inequalities [105]. Mitigating these impacts requires policies such as progressive fuel taxation with rebates, subsidized public transport and car-sharing services, and affordable housing and mixed-use developments in low-income areas [106].

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 [107]. Research suggests that policy fairness and effectiveness appear to be crucial aspects for the design and success of such policies [108].

3.6.2. 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 behaviour change [109–111]. 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" [112]. The new approach to transport pricing would ensure that the relative prices of different transport options reflect the full range of costs and benefits to the consumer, including health, energy, embedded emissions, congestion and other environmental impacts. Restructuring prices include direct subsidy to lock in sustainable travel choices by charging for use of scarce resources at a rising unit rate where more is used. Such pricing mechanisms would therefore expand the traditional notion of road user charging to reflect wider transport and energy system usage and will incorporate thinking on how to avoid increases in demand that may be stimulated by lower motoring costs of electric vehicles. Mode shift policies can improve accessibility and mobility for lower-income groups reliant on public transport, but they also risk gentrification. Improved transport links can increase property values, potentially displacing poorer residents.

Additionally, road user charging and parking restrictions, aimed at reducing single-occupancy car use, may disproportionately impact those who cannot afford alternatives. To mitigate these equity impacts, policies should include affordable active travel infrastructure, targeted public transport investment, and equitable road user charging.

In general, especially where public transport provision has been marketised, greater coordination between local government, business and user groups 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.

3.6.3. *Improve-focussed policies*

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 [113] and CO_2 Performance Standards (Regulation 2019/631 and its predecessors) in the EU [114]. 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.

The UK is one of a few countries that have the stated ambition of ‘phasing out’ fossil fuel vehicles and supporting policy of a ZEVM. Overall, while the policy of phasing out the sale of new petrol and diesel cars and vans by 2030 is ambitious, it is deliverable with strong political will, effective coordination and targeted investments in infrastructure and public engagement. Addressing social equity concerns and ensuring robust legal frameworks will be critical to its success.

While transport electrification combined with a highly renewable grid are crucial, 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 [11,69,115]. Standards for local government, electricity network owners and operators, and private developers will also be important in vehicle charging technology to enable inter-operability. For long-distance freight, the expected decline in the costs of batteries and fuel cells may enable fast market diffusion of zero-emission trucks, but industry and policy will need to prepare for battery-electric trucks with respect to their manufacturing and supply, adequate charging infrastructure and electricity grid expansions, as well as regulation [116]. In general, the shift to BEVs demands significant upgrades to the national grid, increased charging infrastructure, and changes in consumer behaviour, which will require close collaboration across these sectors.

Efficient vehicle technology standards can be supported by national taxation policy [73]. 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 [73]. 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) [117,118]. Crucially, subsidies for EVs should be progressive (i.e. grants, tax credits or low-interest loans for low-income households) and the deployment of charging infrastructure should be distributed equitably [119].

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.

It is worth noting that there may be interactions (either positive or negative) between the ‘A + S’ and ‘I’ pillars of the ASI framework. For instance, the transition to EVs can be classified primarily in the ‘I’ category as EVs are about three times more efficient than their ICE counterparts [120]. However, electrification may lead to rebound effects as cheaper motoring can increase trips and even mode shift towards car travel (A + S) [39], implying a negative interaction with regards to GHG emission reduction. Another example would be road user charging, which is known to have positive interactions between ‘A + S’ impacts (‘disappearing traffic’, short run effect on activity/miles driven) and ‘I’ impacts (more efficient driving, long run effect on ownership of more efficient vehicles) [32].

Table 2 summarises the main policy measures and outcomes for low energy demand mobility.

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, investment in climate and energy businesses [121], 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 the LED 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.

3.6.4. *Revisiting integrated policy making*

The transport sector has rarely been good at integrated policy making and coordination with other sectors or systems, e.g. housing and the circular economy. Climate change is a wicked problem and defies simple solutions (hence why the technology silver bullet may fail). Even if it is not possible to implement all of the policies identified in this research, there is still a clear recognition of the elements of the package which may have to be bound together.

There is comparatively less benefit to constructing high-quality cycling infrastructure and bus lanes if the decreasing cost of car usage with the advent of electric vehicles is not addressed. Transitioning to a more shared and intensively utilized fleet would affect both the charging infrastructure and its utilization. Additionally, land-use changes resulting from *Avoid* strategies will influence servicing strategies. These fragmented approaches are characteristic of current policy responses. However, it is crucial to critically assess their potential efficacy.

A more comprehensive and coordinated approach to transport decarbonisation 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. Without a clear understanding of the benefits of

Table 2
Measures, outcomes and main policies for achieving low energy demand mobility.

Measures and outcomes	Main policies
Transport demand avoidance measures	
No more development on greenfield sites reduces sprawl and trip distances	National and local land use planning
Destination shifting reduces trip distances	Planning for 15-min cities, localisation
Four-day working week and teleworking reduces commuting trips (by 10 % per person by 2030)	Existing trend; employment legislation
Reduced business travel due to greater reliance on video-conferencing	Existing trend; vehicle and fuel taxation
Increased car occupancy from more shared mobility, leading to avoided car trips and reduced congestion	Promoting parking and incentivizing ridesharing, car sharing, car club services
Increased load factors for road freight through improved logistics (from 50 % to max. 60 % on average)	Existing trend; vehicle and fuel taxation
Increased public awareness and higher costs reduce demand for aviation	Aviation taxation; fuel taxation; airport expansion/siting policy
Modal shift measures	
Investment in public & shared transport, walking and cycling increases mode shares for these modes	Public investment; transport planning; private vehicle taxation; fuel taxation
No more major road or airport infrastructure, with focus on maintaining and improving existing infrastructures	Public investment; strategic planning
Increased rail capacity e.g. high-speed rail London to Northern England and Scotland	Public investment
Integrated transport planning in every city and region	Transport governance; land use planning; road use taxation
Increased utilization 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;
Freight consolidation centres in cities and major towns	Investment incentives; transport planning
Increase in light commercial vehicle due to more online shopping	Existing trend; vehicle and fuel taxation; transport planning
Improved vehicle efficiency measures	
Accessible electric vehicle charging infrastructure	Public investment; investment incentives; co-ordinated strategies between stakeholders for public infrastructure
Standardised electric vehicle charging infrastructure	Product standards
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
Non-tailpipe emission reduction of $PM_{2.5}$	Promoting development and use of low-wear tyres; transport/urban planning; RD&D into brake-wear capture technology and improved road surface materials
Buses and taxis all electric by 2030	Product standards; local licensing
New light commercial vehicle all electric from 2030	Product standards; vehicle taxation
Vehicle manufacturing measures	
Increase in recycling rates of vehicles reduces 'new' material demand	Material standards for recycling related to separation
Additional weight saving of car bodies reduces material demand	Product standards related to maximum embodied energy per vehicle, extended to full vehicle life;
Steel fabrication yield improvement in cars reduces 'new' material demand	Product standards related to maximum embodied energy per vehicles, extended to full vehicle life; investment in electric arc furnaces for steel production from scrap materials
Vehicle light-weighting reduces material demand	Variable rates of vehicle taxation based on size, weight and energy use
Smaller vehicle fleet on the road	Car clubs; VAT reductions; public investment in shared mobility; ban ownership and/use of large SUVs

achieving coordination, the motivation for undertaking such a task remains uncertain. This study demonstrates multiple advantages at various scales for a diverse range of stakeholders, both within and outside the transport sector. Outside the sector, a smaller, more multimodal transport system necessitates less (new) infrastructure and fewer construction materials. Increased home- and hub-working impacts housing and alters patterns of domestic versus commercial energy consumption [122]. Importantly, a mixed, coordinated strategy mitigates the significant risk of failing to meet climate objectives, particularly if unproven technologies, such as large-scale carbon dioxide removal, or anticipated social changes, such as shifts in social norms around flying, do not emerge as expected.

3.7. *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, the LED scenarios heavily depend on a multitude of assumptions, including changes in policies, societal behaviours, political will, technological advancements and economic factors. There are uncertainties inherent in 'predicting' future conditions, including the efficacy of any of the energy demand reduction measures. For instance, green H_2 was expected to be used mainly for 'difficult-to-electrify' modes of transport, including some HGV or off-grid applications such as H_2 rail. This was based on the observation that in the UK context, H_2 has been supported and developed at relatively small scale as electric vehicles are seen as the primary solution to climate and energy security, especially given the expected decarbonisation of the grid vis-à-vis challenges to develop a green H_2 based infrastructure at the scale and pace required. This situation may be different in other jurisdictions such as Scandinavia or California, USA. This study followed recommendations by Skea et al. [123] and selected the most appropriate methods and realistic, evidence-led assumptions to deliver plausible scenarios 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 this study may not fully capture the real-world complexities of changing behaviour, especially at the scale and speed assumed. Third, the scenarios in this research assumed the widespread availability and adoption of advanced technologies, such as the electrification of the entire car fleet. While this work considers 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. The study does not incorporate potential impacts of these external factors. Fifth, the research does not extensively address the potential equity implications of the LED scenarios. The impact on different population groups and regions may vary, and issues related to accessibility, affordability, and social justice require further exploration. Sixth, the LED 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. Given that BAU planning may well fall short in meeting carbon budgets, 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. With that comes an acceptance of uncertainty from some of these limitations. It is also necessary, as shown in this work, 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 [124]. Further research could identify the policy areas and areas of social and technological change that have the highest impact. Furthermore, research could assess what would be the sequential suggested implementation, e.g. between 2025 and 2030 and the post 2030 period. Also, further research could investigate equitable policy design, focusing on affordability and accessibility for disadvantaged groups; identify context-specific strategies for different local area types; and investigate methods for increasing public participation in the planning and implementation of transport policies. Some of this work is already occurring, for example, the LED scenarios are currently being localised [125] and investigated with the UK public [126] to understand if a social mandate exists for a low energy demand future.

4. Conclusions

The aim of this research was to investigate the contribution that energy demand reduction in transport can make to improve direct and lifecycle carbon emissions, local air pollution and public health impacts. By employing a structured scenario-based approach, using a comprehensive bottom-up modelling framework and analysing current travel choices in terms of journey purposes, lengths, and modes, this study captured the potential impact of long-term societal and technological changes on travel activity and composition, vehicle fleet evolution and use, energy and emissions impacts, and wider health impacts of changes to physical activity. This analysis incorporated non-price determinants of behaviour (values, norms, fashion, trust, knowledge) and non-consumptive factors (time use, mobility, social networking, policy acceptance). The scenario-based approach enabled a comprehensive assessment of the combined effects of various policy mixes, social changes and technological advancements. This integrated, holistic analysis goes beyond the scope of single-policy analyses and the dominant field of research that investigates technocentric solutions to climate change, air pollution and public health in the sector.

The research found that significant reductions in mobility energy demand of up to 61 % by 2050, compared to baseline levels, are feasible without compromising citizens' access to work, services, and some aspects of their quality of life. While the HA scenario was built on gradual change using existing technology and current social and political framings, the TC storyline assumed more rapid change in travel patterns, mode choice, occupancy levels and technological change, leading to faster transformations and new demand trajectories, particularly in the second half of the 2020s. While the scenarios may not seem different in the long term, the earlier transformation in the TC case translates into significant additional cumulative emissions savings.

The transport energy demand reductions 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 [127]. 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 – a finding that resonates with studies for Germany [31] and globally [30]. These results further 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 the 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 [128].

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 [122]. Whilst there are arguments that scaling up grid provision is technically feasible it is unclear how this will be paid for and by whom [129,130]. An example can be taken of EVs in the UK, where 23 % of households do not own a car and 'socialising' the cost of grid upgrades through electricity bills would thus be profoundly inequitable. General taxation might be more appropriate but the politics are difficult as has been revealed during the energy price spikes following the Russian invasion of Ukraine.

The 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 may be unachievable. In the absence of such reductions, GHG emission reductions in the sector would also rely on complete decarbonisation of a considerably larger energy supply system and larger vehicle fleets. Given the evidence presented here, it may be prudent for the UK Government to develop a detailed 'transport energy demand strategy' and implement supporting policies, with the view to play an important role in achieving emissions reductions particularly in the short to medium term.

The air pollution analysis concludes that while significant reductions in NO_X emissions are achievable, $PM_{2.5}$ emissions, primarily from non-tailpipe sources like tyre and brake wear, remain a persistent challenge. Even with a fully decarbonized vehicle fleet, non-exhaust $PM_{2.5}$ emissions continue to pose health risks, necessitating further clean air measures beyond current technological and societal shifts. Policymakers must therefore prioritize holistic solutions that include promoting smaller, more efficient vehicles, encouraging shifts to public transport and investing in brake-wear capture technology and improved road surface materials to mitigate non-exhaust emissions.

The research also found that a shift towards active travel modes such as walking, cycling and e-biking can lead to substantial health benefits, including a significant reduction in premature deaths and a decline in chronic diseases. Despite the potential risks of increased exposure to air pollution and crash incidents, the benefits of increased physical activity far outweigh these drawbacks in the UK context. However, realizing these benefits will require the implementation of high-quality infrastructure, targeted policy measures and careful urban planning to mitigate risks and ensure that active travel remains a safe and healthy option for the everyone. As we look toward 2050, the continued focus on enhancing safety and reducing pollution exposure will be crucial to maximizing the public health gains from increased active travel.

UK Government initiatives have predominantly prioritized enhancing technological efficiency, often overlooking alternative mechanisms that entail reducing the need for mobility or transitioning to more sustainable modes of transport. Such an approach may lack foresight and may overestimate the real world scale and pace of technological change. Technological advancements inherently trigger behavioural shifts as individuals adjust to the cost and performance differences of new products, such as EVs. This research underscores the necessity for a comprehensive appreciation and promotion of behaviour change, which can mitigate the adverse outcomes associated with maintaining current BAU approaches. What ultimately distinguishes this scenario exercise is the creation of an optimistic and plausible [123] 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 [131]. People may still access local services, leisure activities, and diverse employment opportunities, while enjoying cleaner air and improved mental and physical health.

The feasibility of implementing the policy measures hinges on a comprehensive and coordinated approach, a longstanding challenge in the transport sector despite its conceptual appeal. Importantly, policy may be more effective and acceptable if focussed on co-benefits and quality of life impacts that may be more amenable to citizens and business, namely promoting active living, clean air, safe communities and reduced inequality and social exclusion. So, while transitioning promises numerous benefits, caution is warranted as significant strides are still required to envision and realize these scenarios. The opportunity for transformative change is finite. Focusing solely on rapid electrification without addressing broader energy demands and the comprehensive costs associated with mobility risks constraining lower energy demand scenarios, potentially locking individuals into low-cost e-mobility solutions. Opting for Business as Usual may appear politically expedient but could yield inferior outcomes across various metrics. This research argues that there exists both the potential and the agency to transition towards healthier, more equitable and fulfilling futures with lower energy demand in mobility. The extent to which society seizes this opportunity will profoundly influence our ability to meet the 1.5 °C warming target.

CRediT authorship contribution statement

C. Brand: Writing – original draft, review & editing, Conceptualization, Methodology, Software, Formal analysis, Funding acquisition, Investigation, Data curation, Visualization. **G. Marsden:** Conceptualization, Methodology, Investigation, Funding acquisition, Writing – review & editing. **J.L. Anable:** Conceptualization, Methodology, Investigation, Funding acquisition, Writing – review & editing. **J. Dixon:** Methodology, Investigation, Writing – review & editing. **J. Barrett:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Christian Brand reports financial support was provided by UK Research and Innovation. Christian Brand reports financial support was provided by UK Energy Research Centre. Greg Marsden reports financial support was provided by UK Research and Innovation. Jillian Anable reports financial support was provided by UK Research and Innovation. James Dixon reports financial support was provided by UK Research and Innovation. John Barrett reports financial support was provided by UK Research and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix B. Supplementary data

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Appendix A. Supplementary data

Supplementary Information.

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