Transportation Research Part D 133 (2024) 104311

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Quantifying impacts of sustainable transport interventions in Scotland: A system dynamics approach

Kathleen Davies *, Edward Hart, Stuart Galloway

Department of Electronic and Electrical Engineering, University of Strathclyde, 16 Richmond Street, Glasgow G1 1XQ, United Kingdom

ARTICLE INFO

Keywords:
Vehicle kilometers traveled
Modal shift
Electric vehicles
CO_2 emissions
System dynamics modeling
Transport policy

ABSTRACT

To overcome the challenge transport presents to net zero, the Scottish Government has proposed a series of interventions to significantly reduce transport emissions and car kilometres travelled. This paper develops, validates and applies a system dynamics model of the Scottish road passenger transport sector to interrogate key proposed interventions up to 2030: namely, modal shifting sub-10 km car journeys to active travel, modal shifting medium-length car journeys to buses, achieving a majority electrification of the bus fleet, and replacing 50 % of petrol/diesel cars with electric vehicles. Results indicate government targets can be met, but only as a result of multiple interventions. Modal shifting of medium-length car journeys and private car electrification are predicted to be the most effective interventions for emissions reduction, although these measures alone do not attain reduction targets. Results further indicate that realising the reduction in car kilometres does not guarantee the emissions target will also be achieved.

1. Introduction

The biggest emitting sector of greenhouse gases in Scotland is domestic transport (Scottish Government, 2023a), with road travel accounting for 66 % of all transport-related emissions (Transport Scotland, 2023d). Therefore, transport poses a significant barrier to the achievement of net zero, the legally binding deadline for which is 2045 in Scotland. Furthermore, the reduction of emissions is crucial to improving air quality, public health and fostering social equity among other positive externalities (Woodcock, et al., 2009; Milner, et al., 2020; Douglas, et al., 2023).

In response to the environmental challenges posed by travel, the Scottish Government has set a transport-specific target to reduce emissions associated with transit by 56 % by 2030, comparative to a 1990 baseline (Transport Scotland, 2023c). As a mechanism through which to achieve this, initiatives supporting a 20 % reduction in car kilometres travelled by 2030, compared to 2019 levels (Transport Scotland, 2022b), have been outlined by the Scottish Government. These include zero-emission car clubs (Transport Scotland, 2022a) and multiple localised pilot schemes of Mobility as a Service (MaaS) (Transport Scotland, 2023b), where generally a singular platform grants access to live travel information and the ability to plan, book and pay for travel services across multiple modes of transport. The 20 % car kilometre reduction target was informed by previous work (Element Energy, 2021) seeking to understand legislative outcomes necessary to meet government mandated emissions targets.

Decreased usage of the private car is thought not only to reduce transport emissions but also to achieve a more equitable transport

* Corresponding author.
E-mail addresses: kathleen.davies.2017@uni.strath.ac.uk (K. Davies), edward.hart@strath.ac.uk (E. Hart), stuart.galloway@strath.ac.uk (S. Galloway).

https://doi.org/10.1016/j.trd.2024.104311
Received 4 March 2024; Received in revised form 27 June 2024; Accepted 28 June 2024

network, as a move away from a car-centric system can be facilitated. A private car orientated transport system can disproportionately disadvantage those less likely to own a car (Douglas, et al., 2018; Douglas, et al., 2023) such as women, the elderly, the disabled, those with lower incomes and some ethnic minority groups (Transport Scotland, 2022b). However alternative modes, namely public transport, also pose barriers to certain groups such as cost and availability of services (Martiskainen, et al., 2023; Sustrans, 2016) and safety concerns (Skellington Orr, et al., 2023).

It is acknowledged by the Scottish Government that certain groups (e.g. those living in remote or rural areas) will be unable to reduce their car kilometres to the same extent as others. Therefore the 20 % car kilometre reduction target is a nationwide average goal, rather than a goal for each individual (Transport Scotland, 2022b). Although it is accepted that for some journeys the car will remain the optimal mode of transport, ideally these journeys will eventually be completed by electric vehicles (EVs). However, those least able to pay face significant barriers to EV access, namely the high ticket price associated with owning an EV, access to residential or workplace charging facilities, disparities between public and private charging tariffs and the disproportionate distribution of public charging infrastructure in more affluent areas (Hardman et al., 2021; Transport Scotland, 2023a).

To accomplish the car kilometre reduction target, visions of a modal shift away from private car usage and towards active travel (i.e. walking, wheeling if referring to wheelchair users, cycling, and the possible inclusion of electric micromobility modes such as electric bicycles or scooters (Christoforou, et al., 2021; Cuffe, 2018)) and public transport are set out in the National Transport Strategy (Transport Scotland, 2020b). Additionally, a transition away from petrol and diesel cars and towards EVs is envisioned. The overall aim is to achieve a transport system where active travel and public transport modes are prioritised over private mobility such as private cars (particularly single occupancy cars) and motorcycles, as illustrated by the Sustainable Mobility Hierarchy in Fig. 1. This hierarchy conveys that active travel modes should be most highly prioritised, meaning that it is envisioned that this mode should be the first port of call for making journeys. Public transport closely follows active travel in the hierarchy, which in turn should be prioritised over shared transit, such as taxis or private coaches, and private mobility such as the private car.

Specifically, the National Transport Strategy (Transport Scotland, 2022) stipulates that shorter journeys should ideally be made by active travel; shorter to medium journeys should ideally be made via public transport; longer journeys should ideally be made by public transport and low-emission vehicles; and that most buses will be zero-emission by 2024. The Roadmap to Widespread Adoption of Plug-in Vehicles (Transport Scotland, 2013) also outlines the aspiration that there should be a 50 % reduction in the number of petrol and diesel cars by 2030, with many of these being replaced by EVs.

Previous work has considered the impacts of sustainable mobility policies (e.g. MaaS) (Cisterna, et al., 2022; Labee, et al., 2022; Zhao, et al., 2021) in various countries and regions. Although similar policy has been mandated in Scotland to tackle the barrier that transport poses to achieving a sustainable society, the wider impacts and efficacy of such legislation here is relatively unexplored. The current paper therefore addresses the resulting need to rigorously quantify the likely ability of planned interventions to reduce car kilometres travelled and, in turn, the emissions resultant from transport. With other international governments acknowledging the significant obstacle that transport poses to their own emission reduction plans and adopting similar strategies to Scotland (e.g. the Irish Government have also outlined a similar target to reduce car distance travelled by 20 % by 2030 in their Climate Action Plan for Transport (The Irish Government, 2023)), the case for thoroughly investigating such interventions is further strengthened.

This paper aims to evaluate the implications of scenarios relevant to the Scottish Government vision for a sustainable transport network. Specifically, this will focus on the modal shifting of car journeys under 10 km to active travel; the modal shifting of car journeys between 10 km and 40 km to bus travel; the proportion of buses that are electric reaches 60 % by 2024; and a 50 % reduction in the number of petrol and diesel cars, with these cars being replaced by EVs, in line with government aspirations (Transport Scotland,

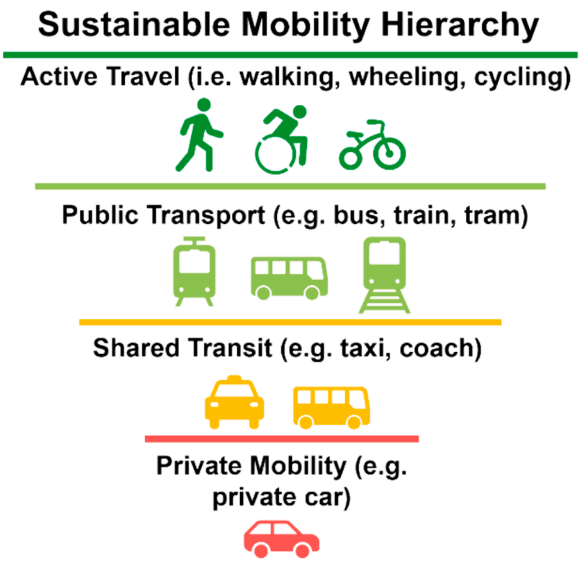

Fig. 1. ‘Sustainable Mobility Hierarchy’, adapted from (Transport Scotland, 2020b).

2020b; Transport Scotland, 2013). The presented analysis utilises system dynamics modelling, motivated by its successful application to other research problems in the transport sphere (Zhang, et al., 2022; Martensson, et al., 2023; Eisenkopf & Burgdorf, 2022; Nassar, et al., 2023; Wen & Wang, 2023). System dynamics is a powerful, time-based modelling technique that can effectively manage feedback loops and non-linear relationships, aspects which are essential for the exploration of policy impacts and possible future scenarios associated with the Scottish road passenger transport sector.

With emission reduction deadlines rapidly approaching, and with the cumulative effect of emissions making prompt action imperative (Element Energy, 2021), it is pertinent that pathways to achieving these pressing targets are evaluated, including assessment of the likelihood that emission reduction targets will be met via planned interventions and government aspirations in Scotland, along with the potential efficacy of planned emission reduction pathways.

In summary, the presented analysis models the impact of the following interventions, based upon Scottish Government ambitions, on the road passenger transport system in Scotland:

- Modal shifting of car journeys under 10 km to active travel
- Modal shifting of car journeys between 10 km and 40 km to bus
- Proportion of buses that are electric reaches 60 % by 2024
- The number of petrol/diesel cars reduces by 50 % by 2030, with those petrol/diesel cars being replaced by EVs

In doing so, this paper seeks to answer the following research questions: 1) What is the likelihood that planned sustainable transport interventions will be sufficient to meet government mandated emission reduction targets? 2) What is the likely efficacy of these planned interventions in reducing emissions?

The remainder of the paper is structured as follows: Section 2 provides a background of this study, highlighting relevant previous works; Section 3 details the methods used, namely system dynamics modelling and scenario-based analysis; Section 4 details the results and provides a discussion of the findings; Section 5 explores the implications that these results have for policy, transport planning and future work, and Section 6 gives a conclusion.

2. Background

To achieve emission reduction targets in Scotland, prioritisation of active travel and public transport over the private car is envisioned. While some extant literature (Rabbitt & Ghosh, 2016; Velez & Plepys, 2021; Cisterna, et al., 2022; Labee, et al., 2022; Zhao, et al., 2021) explores the impact and effectiveness of planned policies in Scotland targeting reduced car reliance such as supports for MaaS and car clubs in other countries, these studies are often single policy focused, region specific and in many cases reliant on pilot projects as these initiatives are still in infancy.

Main findings from these works, which span geographical focuses of Ireland, the Netherlands, Germany and Sweden, include that car clubs pose the potential for increased use of more sustainable modes, reduced overall travel emissions and decreased car ownership (Rabbitt & Ghosh, 2016) but crucially, a multifaceted approach combining fleet electrification and reduced car reliance gives the most effective emission reduction (Velez & Plepys, 2021). MaaS has been found by multiple studies to effectively promote a modal shift towards public transport and alternatives to the private car (Cisterna, et al., 2022; Labee, et al., 2022; Zhao, et al., 2021) by increasing the attractiveness, convenience and connectivity of these other modes. There is also evidence of the possibility that MaaS could drive a reduction in car ownership (Zhao, et al., 2021), however, this is contested by other literature (Orozoco-Fontalvo & Moura, 2023; Pritchard, 2022).

In Scotland, upon committing to reaching net zero by 2045, the national transport agency, Transport Scotland, commissioned a study (Element Energy, 2021) aiming to comprehend the policy outcomes necessary to achieve emission reduction targets in Scotland. This study considered broad scenarios including passenger and freight travel across road, rail, air and marine modes which featured 'rapid introduction' of low/zero-emission vehicles, modal shifting, and reduced overall travel demand.

The scenarios modelled iteratively increased the number of features included (e.g. the first scenario featured the introduction of low/zero-emission vehicles, the next scenario featured both the introduction of low/zero-emission vehicles and modal shifting etc.), however, each feature was not simulated in isolation and so their individual impact was not explored. Additionally, the study does not provide detailed pathways to achievement of the scenario features.

It was found that only the scenario including all the features (i.e. low/zero-emission vehicles, modal shifting and reduced travel) sufficiently met emission reduction targets, echoing other work (Velez & Plepys, 2021) that highlighted the necessity for comprehensive approaches in tackling emissions. A key outcome of this work was the recommendation of instating a 20 % reduction in car kilometres travelled target, which was consequently adopted by the Scottish Government.

A subsequent study (Scottish Government, Ricardo and UK Centre for Ecology and Hydrology, 2024) investigated the ability of planned policy packages (e.g. financial investments, legislative support for programmes) to reduce transport emissions. This found that legislation supporting a transition to EVs facilitated the most significant emission reduction, whilst policy packages broadly supporting a car kilometre reduction and bus fleet electrification also gave notable but less significant emission reductions. A specific breakdown of the impact of modal shifting policies was not provided.

Other work (Broadbent, et al., 2022) highlights the importance of clean energy generation alongside transport electrification to harness the full potential this has to contribute to achievement of net zero. The Scottish electricity supply is generated mainly from renewable and low carbon sources, with approximately 88 % of electricity being generated from these sources in 2021. Wind, nuclear and hydropower were the most significant contributors to generation in this year, contributing circa 41 %, 30 % and 10 % of the total generation respectively (Scottish Government, 2023c). Additionally, the Scottish grid carbon intensity has been maintained below 50 gCO_2/kWh since 2017 according to the Scottish Government's Climate change monitoring report 2023 (Scottish Government, 2023d).

Considering transport systems and future scenarios requires a powerful method. As has been indicated, analysis will be undertaken using system dynamics modelling, which captures cause and effect relationships between variables within the system and can provide a holistic analysis by combining diverse variables (e.g. technical, environmental, social and/or economic). This, in turn, allows for scenario-based analyses which facilitate the interrogation of realistic policy landscapes. Previous work (Zhang, et al., 2022) studied the transport network in rural China, using system dynamics techniques to understand the impact of sustainable transport policy, namely the provision of subsidies for low emission vehicles and the electrification of the bus fleet. The developed system dynamics model concisely encapsulates the makeup of the transport system and how it operates and emits CO_2, and included core variables capturing population, economy, modes of transit, road infrastructure, distance travelled by each mode, CO_2 emissions and legislation. Scenario-based analysis was applied, forecasting the impact of varying degrees of low-emission vehicle subsidy provision and electric bus penetration on CO_2 emissions, bus usage and proportion of internal combustion engine vehicles. Various other works have used system dynamics to consider the impact of initiatives targeting reduced travel emissions in various locations and with varying policy designs. For example, studies have investigated the wider impacts of MaaS provision (Martensson, et al., 2023), modal shifting of long-distance car journeys to rail (Eisenkopf & Burgdorf, 2022), modal shifting for freight transportation (Nassar, et al., 2023) and public transport electrification (Wen & Wang, 2023) in the geographical framework of Sweden, Germany, Brazil and China respectively.

The ability of system dynamics to handle diverse variable sets and intricate relationships makes it singularly attractive for the analysis of complex transport network and policy problems. Furthermore, system dynamics can effectively manage feedback loops and accommodate scenario-based analysis, allowing for system variables' responses to policy intervention and trends over time to be captured (Shepherd, 2014) and making this method applicable to this problem context. A 'stock and flow' diagram acts as the foundation of system dynamics modelling. There are several different variables included in these diagrams, as demonstrated by Fig. 2, which gives an example of a 'stock and flow' structure that could feature in a more expansive 'stock and flow' diagram. Specifically, stocks (i.e. the variables in boxes) represent accumulations; flows (i.e. double-lined black arrows) represent rates; and limits (i.e. cloud-like structures) signify that what is fed into or out of these points are outwith the system's boundaries (Shepherd, 2014). Variables that may be outside system boundaries are deemed of low/negligible relevance to the problem considered. Stock variables are assigned an initial value. The value of stock variables are then influenced by flows (Ford, 2019) and are the integral of flows passing into the stock variable minus flows passing out of the stock variable plus the initial value (Shepherd, 2014). While stocks are indicative of the system's state, flows are indicative of activity within the system (Ford, 2019). All other variables in the model are auxiliary variables and the blue single-line arrows connecting them to other model features indicate causal relationships. Deterministic equations describe the relationships between linked variables. In summary, previous literature (Rabbitt & Ghosh, 2016; Velez & Plepys, 2021; Cisterna, et al., 2022; Labee, et al., 2022; Zhao, et al., 2021) explores some of the impacts of sustainable transport policies that are planned in Scotland. However, these works are often focused on solitary initiatives and are localised, considering different territories and regions, which may possess different complex geographies, varying cultural attitudes and mindsets (regarding transport), and different climates and socio-economic characteristics compared to Scotland. While other work that is centred on Scotland forms the basis of the government's car kilometre reduction target (Element Energy, 2021), it does not explore the efficacy of individual interventions or provide specified pathways to achievement of the modelled scenario features. Other work (Zhang, et al., 2022; Martensson, et al., 2023; Eisenkopf & Burgdorf, 2022; Nassar, et al., 2023; Wen & Wang, 2023) considering impact of interventions on transport systems uses system dynamics techniques which has been shown to be an effective method for this application, especially for simulation of scenarios.

3. Methodology

To interrogate the efficacy and likely ability of planned interventions to reduce transport emissions in Scotland, a system dynamics model was developed using Simantics System Dynamics Version 1.35.0 open-source software (Simantics, 2014). As discussed, system dynamics techniques were utilised for their suitability when conducting scenario-based and policy related analyses in the transport sphere (Zhang, et al., 2022; Martensson, et al., 2023; Eisenkopf & Burgdorf, 2022; Nassar, et al., 2023; Wen & Wang, 2023).

The high-level structure of the developed system dynamics model was informed by previous work (Zhang, et al., 2022). The model captures socioeconomic variables; the composition of the road passenger transport fleet; the vehicle kilometres travelled by the

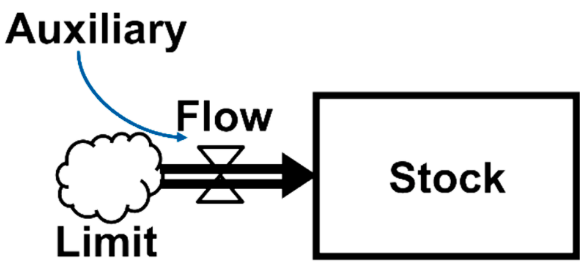

Fig. 2. Example of variables and structure that may feature in a system dynamics stock and flow diagram.

relevant modes and their emissions, and is used to make forecasts of trends of these variables under different scenarios. The following subsections detail the overall research methodology, including model development, validation and scenario specification.

3.1. Model development

The model developed in this study was heavily adapted from that in (Zhang, et al., 2022), in order to be applicable to Scotland's road passenger transport system. Scotland equivalent data (detailed in Appendix A) on variables used in the previous work's modelling environment was collected and interrogated, including application of regression techniques, to understand the nature of relationships present in the Scottish context. Subsequent structural adaptations were made, informed by these relations, and deterministic system dynamics equations describing interactions between variables were derived, also via regression analyses of Scottish transport and socioeconomic data.

Fig. 3 illustrates the model 'stock and flow' structure which underpins the modelling framework, showing all model variables and outlining the modules contained, namely a socioeconomic module, vehicle fleet and infrastructure module, vehicle kilometre module and emissions module. These modules feed into each other in this order from left to right. The following subsections detail the model configuration. These are followed by details of the derivation of the deterministic equations that define the relationships between linked variables in the system.

3.1.1. Socioeconomic module

The socioeconomic module captures population and gross domestic product (GDP), which are key variables used to drive the modelling. It should be noted that GDP accounts for onshore GDP only. The socioeconomic module feeds into the vehicle fleet and infrastructure module and informs the forecasting of variables contained there.

3.1.2. Vehicle fleet and infrastructure module

The vehicle fleet and infrastructure module projects the share of each vehicle type, namely motorcycles, EVs, and petrol/diesel cars, in the road passenger transport system. Vans, hybrid cars, range extended EVs, and diesel and electric motorcycles were not included. The values for each vehicle type were based on the number of licensed vehicles in Scotland. It should be noted that it is possible that there may be vehicles licensed here that are operated elsewhere (e.g. in other nations in the UK) and vice versa. There are two scenario variables in this module, 'petrol/diesel car shift' and 'electric vehicle shift'. These variables ultimately influence the number of petrol/diesel cars and the number of electric vehicles, in line with the applied scenarios detailed in Section 3.3. The composition of the vehicle fleet is used to predict the distance travelled by each vehicle type.

It is noteworthy that although buses are not featured in this module, they are included in the model, however, due to the relatively stable nature of bus vehicle kilometres travelled in Scotland (i.e. the bus distance travelled has steadily decreased from 346 to 336 million vehicle kilometres between 2010 and 2019 (Transport Scotland, 2022c)), this variable is treated as a constant. In this time frame (i.e. 2010 to 2019), bus passenger journeys also decreased from 430 to 363 million journeys (Transport Scotland, 2022c). As bus service provision (i.e. bus distance travelled) decreased by approximately 2.9 %, the bus usage (i.e. number of passenger journeys) saw a greater decrease of circa 15.6 %. Therefore, it was assumed that there is spare capacity on existing buses and the variable was assigned the average value of bus vehicle kilometres travelled across the time period 2010 to 2019 (Transport Scotland, 2023d). The bus mode is therefore represented in the vehicle kilometres module instead.

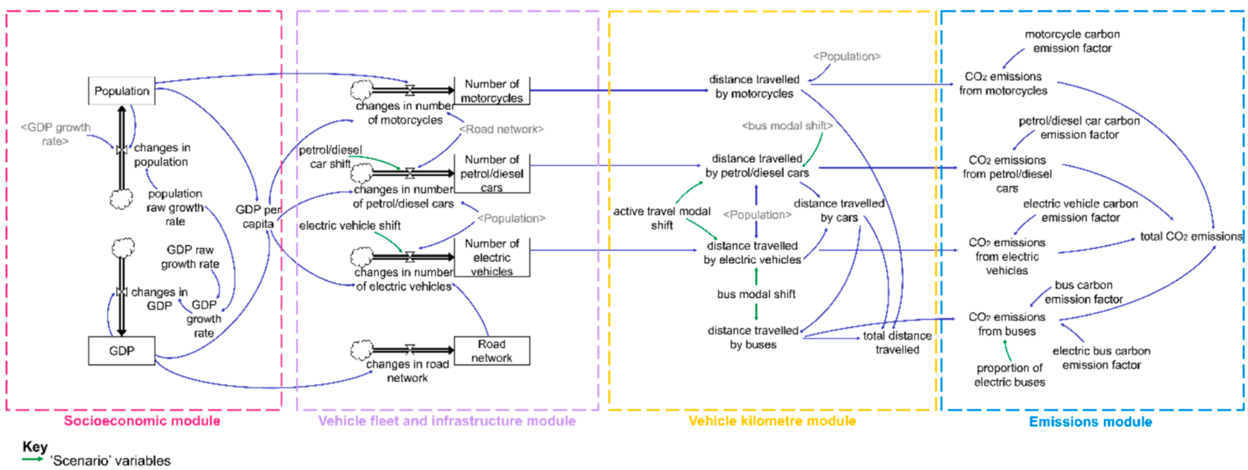

Fig. 3. Stock and flow diagram developed and validated to capture the Scottish road passenger transport system, high level structure. adapted from (Zhang, et al., 2022)

3.1.3. Vehicle kilometre module

The vehicle kilometre module uses the composition of the vehicle fleet to forecast the vehicle kilometres travelled by each vehicle type. It is assumed that the proportion of each car fuel type translates directly to the proportion of all car kilometres travelled that the fuel type is responsible for (i.e. if 90 % of all cars are petrol/diesel cars, then petrol/diesel cars are responsible for 90 % of all car kilometres travelled). There are two scenario variables in this module, 'active travel modal shift' and 'bus modal shift'. These variables influence the distance travelled by cars and buses respectively. The distance travelled by cars (petrol/diesel and EVs) is a key output of this module.

3.1.4. Emissions module

The emissions module uses the predicted vehicle kilometres of each vehicle type to forecast the resultant emissions of each category using vehicle-specific carbon emission factors. The carbon emission factors (UK Government, 2023) used in all simulations for petrol/diesel cars and motorcycles were the values provided for 2023, therefore it was assumed that vehicle efficiency was constant throughout the simulation period. Average vehicle size was also assumed. Additionally, for 'petrol/diesel cars', the carbon emission factor for petrol was used as this was the slightly larger of the two by a very small margin. Carbon emission factors of electric buses and EVs were included to capture emissions associated with charging, and were calculated (Davis, 2011) by multiplying the average efficiency of the vehicle (car (Electric Vehicle Database, 2023); bus (United States Department of Transportation, 2018)) by the maximum Scottish grid carbon intensity between 2017 and 2020 according to the Scotland Climate Change Monitoring Report, 2023 (Scottish Government, 2023a). It should be noted that the efficiency of electric buses was informed by a study (United States Department of Transportation, 2018) featuring a relatively small sample size, short time frame and a geographical location different from that of this work. There is one scenario variable in this module, 'proportion of electric buses'. This variable influences the CO_2 emissions of buses. The total CO_2 emissions of the Scottish road passenger transport system is a key output in this module.

3.2. Modelling deterministic relationships

The deterministic equations that describe the relationship between linked variables in the model were formulated through regression modelling using MATLAB (MathWorks, 2023) and Scottish socioeconomic and transport data. Different forms of regression (e.g. linear, polynomial, exponential) were trialled to find the most appropriate expression for each variable. In trialling these different forms of regression for each variable, the model was calibrated to give a mean absolute percentage error of less than 10 % during model validation which is discussed further in Section 3.4. The regression type that gave the lowest mean absolute percentage error for each variable was selected. Multiple linear regression was used for all variables with the exception of 'change in number of EVs', which used exponential regression. Table A.1 in Appendix A details the equations, resulting from this regression analysis, utilised in the system dynamics model. Regression data sources are also provided.

Fig. 4 shows the categorisation (i.e. exogeneous, endogenous, and scenario variables) of the variables contained within the developed system dynamics model. The scenario variables control the application of the scenario-based analysis, further described in Section 3.3. The exogenous variables are externally determined and have the ability to impact the system but are not themselves impacted by the rest of the system. In contrast, the endogenous variables are determined within and impacted by the system (Ford, 2019). Table B.1 in Appendix B provides the initial conditions for stock variables for both the validation and scenario analyses, and

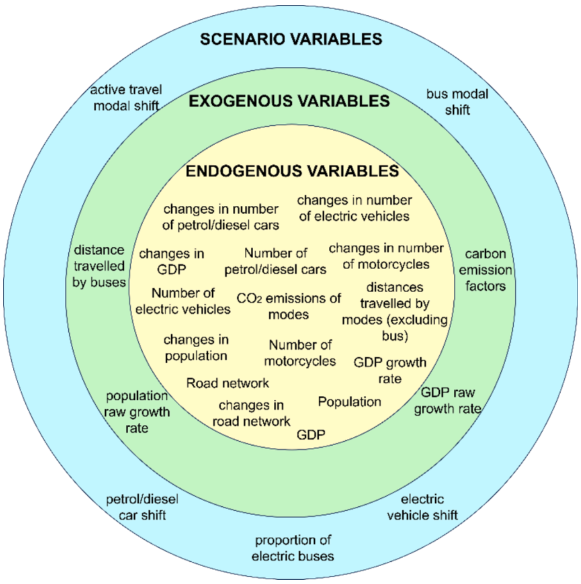

Fig. 4. Bullseye diagram separating the model variables into categories of scenario, exogenous and endogenous variables.

Table C.1 in Appendix C provides the exogenous variables' inputs for both the validation and scenario analyses. Where applicable, data was generally taken for the fourth quarter of each given year.

3.3. Modelling scenarios

The model was used to make future predictions under different scenarios for the period 2022 to 2030, with 2022 being taken as the start point as this was the most recent data available. Alongside a Business As Usual (BAU) scenario base-case, which assumes no further intervention is taken, four additional scenario components were devised and named 'A', 'B', 'C' and 'D'. These components were informed by aspirations outlined in Scottish Government policy. Table 1 describes each component and provides details of their policy foundations.

All scenarios assume steady, incremental progress in achieving the aspirations within the set time frame (i.e. 2022 to 2030). For scenario components 'A' and 'B', numerical inputs were determined through distributional analysis of data on the proportion of journeys made according to distance travelled and mode from the Scottish Household Survey 2021 (Transport Scotland, 2023e) (full mathematical derivation in Appendix D). The Scottish Household Survey is used by the Scottish Government as a foundation for data-driven policy formulation. The 2021 edition of this was used as it provided the latest data, however, it should be noted that the ongoing COVID-19 pandemic had impacts on data collection methods. Additionally, the data used combined both cars and vans (which are not included in the model). It is assumed in scenario components 'A' and 'B' that EVs and petrol/diesel cars complete the same proportion of journeys within the scenario-specific distance brackets.

For scenario component 'C', it was assumed that having electric buses achieve a proportion of 60 % of the entire bus fleet in steady growth increments would fulfil the requirement that most buses be zero emission by 2024. A steady increase in proportion of electric buses continues beyond 2024 until all buses are electric in this scenario component. Similarly, for scenario component 'D' the number of petrol/diesel cars was decreased in steady increments until a 50 % reduction was achieved in 2030, compared to a 2022 baseline. The incremental reductions in petrol/diesel cars were added to the 'Number of EVs' to simulate the replacement of these petrol/diesel cars with EVs. Although the government aspiration (Transport Scotland, 2013) specifies the targeted phasing-out of petrol/diesel cars will be focused in urban localities, there are indications in other policy documentation (Scottish Government, Ricardo and UK Centre for Ecology and Hydrology, 2024) that it is the ambition of the Scottish Government to phase out the overall need for new petrol/diesel cars by 2030. Therefore, the modelled scenario accounts for a 50 % reduction in petrol/diesel cars across Scotland as a whole. The inputs for scenario variables are detailed in Table E.1 in Appendix E. For the BAU and scenario simulations 'raw GDP growth rate' variable input, there was no data available for 2030, therefore it was assumed that the 2030 GDP growth would remain consistent with the 2029 value.

The fifteen possible combinations of scenario components 'A', 'B', 'C' and 'D' (i.e. 'A', 'A + B', 'A + B + C' etc.) were applied to the model. The efficacy of each scenario set was compared to a targeted value of a 56 % reduction in emissions of the modes considered in the system, as required by the government mandated target (Transport Scotland, 2023c) (see Appendix F for details).

3.4. Model validation

The model was validated by conducting a historical consistency test, comparing simulated values with actual recorded data for the period 2010 to 2019. The years 2020 and 2021 were excluded from the model validation test time-period as during these years, fundamental relationships (e.g. the relationship between GDP and population) broke down due to the outbreak and impact of the COVID-19 pandemic.

On completing the 2010 to 2019 simulation, the mean absolute percentage error was used to compare the simulated and true values, allowing for the quantification of modelling errors. The mean absolute percentage error is given by Equation (1) where N is the number of observations, A_t is the actual reported historical value, and M_t is the modelled value given by the system dynamics simulation.

Table 1
Interventions considered and the policy documents that informed them.

Scenario Component/ Intervention	Description	Policy Foundation
'A' – Modal shift to active travel	All car journeys under 10 km are now completed by active travel	Shorter journeys should ideally be made via active travel, as set out by the National Transport Strategy (Transport Scotland, 2022)
'B' – Modal shift to bus	All car journeys between 10 km and 40 km are now completed by bus	Medium-length journeys should ideally be made via public transport, as set out by the National Transport Strategy (Transport Scotland, 2022)
'C' – Bus electrification	60 % of buses are electric by 2024	The majority of buses should be zero emission by 2024, as set out by the National Transport Strategy (Transport Scotland, 2022)
'D' – Shift to EVs	There is a 50 % reduction in the number of petrol/diesel cars by 2030 compared to 2022 levels, with all of those petrol/diesel cars being replaced by EVs	The phasing out of half of all fossil-fuelled vehicles should be achieved by 2030 in urban regions, as set out by the Roadmap to Widespread Adoption of Plug-in Vehicles (Transport Scotland, 2013)

$$MeanAbsolutePercentageError = \frac{1}{N}\sum_{t=1}^{N}\left|\frac{A_t - M_t}{A_t}\right| \tag{1}$$

The maximum percentage error was also calculated. As mentioned, sources of the historical data, which was used to inform the model structure and validate the model, and the stock and exogenous variable inputs for the model validation are given in Appendices A, B and C respectively. No scenario influences were present during model validation.

3.5. Model sensitivity testing

A sensitivity test was conducted to test the model's response to small changes in the inputs. Scenario 'A' inputs were varied such that the car journeys to be modal shifted to active travel were all those under 5 km, to allow results for car kilometres travelled and travel emissions to be compared with the original scenario 'A' where the cut-off was 10 km. Similarly, scenario 'D' inputs were varied such that the petrol and diesel cars to be shifted to EVs were 10 % higher and lower than the original inputs for scenario 'D'. These variables were chosen to be varied due to the direct influence they have on the key modelling outputs and their specific relevance to policy intervention. A sensitivity test is an important procedure for investigating the robustness of the model and ensuring small changes in inputs do not give radically different results. For the model to be considered reliable, the small changes in inputs should give stable or predictable changes in results.

4. Results and discussion

To investigate the potential efficacy of and likelihood that planned interventions can achieve government mandated transport emission reduction targets in Scotland, a system dynamics modelling framework and scenario-based analysis has been undertaken, as described in Section 3. The following subsections detail the results obtained for the model validation test; the model sensitivity test; the total emissions of the road passenger transport system and the car kilometres travelled in Scotland under the modelled BAU scenario and scenarios involving sustainable transport interventions.

4.1. Model validation

Table 2 gives the mean absolute percentage error found for each stock variable in the model validation test, which compared modelled values against actual recorded data (the sources of which can be found in Appendix A) across the period 2010 to 2019. All mean absolute percentage error values are below 10 % and so the model is considered valid.

The model has therefore been validated across a nine-year time period (i.e. 2010 to 2019). While the low mean absolute percentage error values indicate that the modelling framework is a good fit and appropriate for the application of the future simulations across an eight-year period (i.e. 2022 to 2030), it should be noted that application to larger future projections that go beyond 2030 may give more significant error.

The maximum absolute percentage error is also provided for context to give an indication of the upper limit of the model's inaccuracy. Similarly, the maximum absolute percentage error is below 10 % for all stock variables, with the exception of the 'Number of EVs' variable. This highlights that although the model can generally accurately forecast the 'Number of EVs' (as evidenced by the low mean absolute percentage error value), there are occasions where the modelled values could have higher error.

4.2. Model sensitivity

Tables 3 and 4 give the results of the sensitivity test. The small changes in variable inputs resulted in steady, predictable changes in outputs. A more intensive transition to EVs resulted in reduced emissions, as expected. Similarly, a less intensive transition to EVs resulted in increased emissions. In terms of adjusting the journey distance to be modal shifted to active travel, a reduction in car kilometres to be modal shifted resulted in increased travel emissions and car kilometres travelled, also as expected. Therefore, the model may be considered appropriately robust since input and modal shift differences have been shown to influence predictions in a steady and predictable manner that does not dramatically change the interpretation or conclusions of these analyses.

Table 2
Validation test results of Mean Absolute Percentage Errors and Maximum Absolute Percentage Errors for stock variables.

Variable	Mean Absolute Percentage Error	Maximum Absolute Percentage Error
Number of petrol/diesel cars	0.99 %	1.98 %
Number of motorcycles	5.20 %	8.73 %
Number of EVs	8.88 %	22.45 %
Road network	0.02 %	0.15 %
Population	0.18 %	0.32 %
GDP	0.54 %	1.96 %

Table 3
Sensitivity test results when inputs for scenario component 'D' were varied.

	2030 Transport Emissions (MtCO2)	Percentage Difference with respect to 'D' 2030 Emissions
D	4.523	–
+10 %	4.302	−4.878 %
−10 %	4.743	4.878 %

Table 4
Sensitivity test results when inputs for scenario component 'A' were varied.

	2030 Transport Emissions (MtCO2)	2030 Car Distance Travelled (million vehicle km)	Percentage Difference with respect to 'A' 2030 Emissions	Percentage Difference with respect to 'A' 2030 Car Kilometres
A	7.686	49,834	–	–
5 km modal shift	8.293	54,042	7.888 %	8.443 %

4.3. Total road passenger transport emissions

The model predicts the emissions of road passenger transport in Scotland between 2022 and 2030 under the implementation of the interventions considered in this study (see Section 3.3). The fifteen possible combinations of interventions 'A' (modal shift to active travel), 'B' (modal shift to bus), 'C' (bus electrification) and 'D' (shift to EVs) have been grouped in result sets of single interventions, double interventions, and triple/quadruple interventions to communicate the result more clearly. The BAU base-case is included in each result set for reference. The emissions of each scenario set are compared to a 56 % reduction compared to 1990 levels (as mandated by the Scottish Government (Transport Scotland, 2023c), see Appendix F) and this target threshold is represented on each plot by a black horizontal line.

Fig. 5 shows the application of each scenario component in isolation. The model predicts all interventions will facilitate a decrease in emissions with respect to the BAU case, but only scenario components 'B' and 'D' are projected to give a decrease in emissions over time. This implies that encouraging modal shifting to buses for medium-length car journeys and transitioning away from petrol/diesel cars to EVs are likely to be the most effective intervention strategies.

By 2030, it is predicted that there will be 8.8MtCO_2 of emissions from road passenger transport in Scotland under the BAU base-case. Scenario components 'A', 'B', 'C' and 'D' are projected to give emission reductions of 12.5 %, 35.8 %, 4.7 % and 48.5 % respectively, compared to the 2030 BAU emissions predicted by the model. Scenario component 'D' initially has a more modest impact on emissions but this quickly accelerates over time to give the greatest emission reduction compared to BAU. Scenario components 'B' and 'D' are forecast to give emission reductions of 11.7 % and 29.2 % respectively with respect to the road passenger transport emissions in 1990. As demonstrated by Fig. 5, no individual intervention achieves the 56 % reduction in emissions target, indicating that tackling transport emissions is not a single-solution problem.

Fig. 6 shows the results of the application of scenarios grouped in pairs. The model forecasts greater emission reductions in these cases compared to application of individual scenario components, as would perhaps be expected. Almost all pairs of scenario components are projected to facilitate a decrease in emissions with respect to time, however there are still no cases where the emission

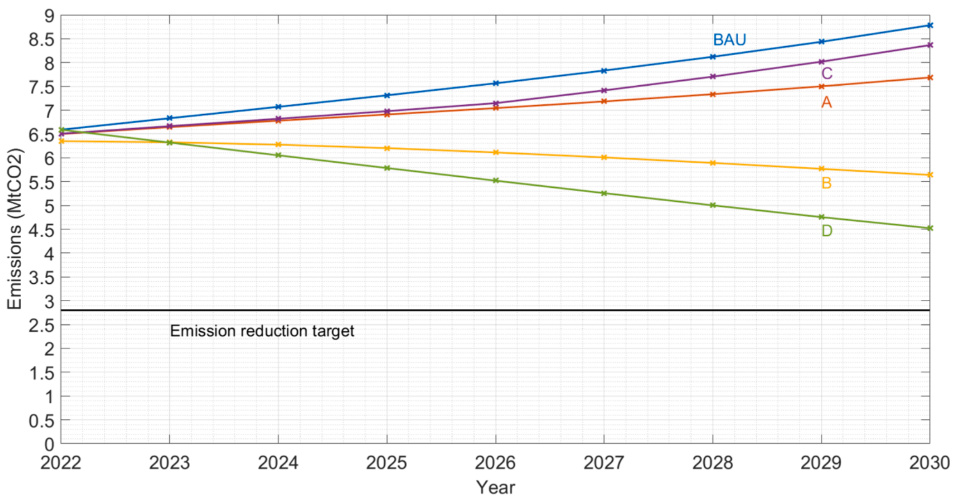

Fig. 5. Emissions trends predicted by the model under implementation of individual interventions.

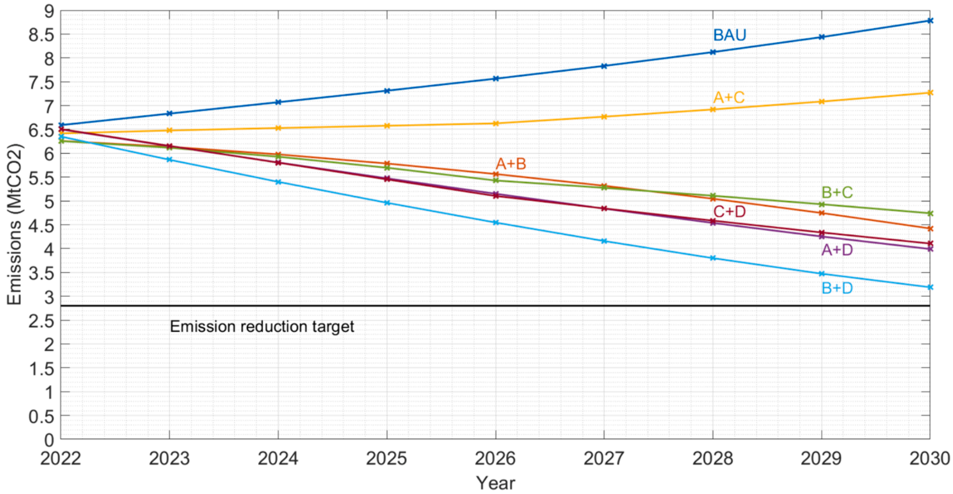

Fig. 6. Emissions trends predicted by the model under implementation of pairs of interventions.

reduction is predicted to be achieved. Scenario 'A + C' is not predicted to drive a decrease in emissions over time and is likely to give the smallest decrease in emissions with respect to the BAU base-case, specifically a 17.2 % decrease. Meanwhile, scenario 'B + D' is projected to give the most significant decrease in emissions, 63.7 % with respect to BAU, and the remaining scenarios (i.e. 'B + C', 'A + B', 'C + D' and 'A + D') are forecast to result in between 46 % and 54.6 % emission reductions compared to the BAU base-case.

Fig. 7 illustrates that groupings of three and four interventions are predicted to give greater emission reductions again, in comparison to single and pairs of interventions. All scenarios in this instance are forecasted to facilitate a decrease in emissions with respect to time and the combination of all four scenario components is predicted to give the largest emission reduction, unsurprisingly. The model projects that in three cases, 'A + B + D', 'B + C + D' and 'A + B + C + D', the 56 % emission reduction target is met. These combined scenarios were predicted to enable 70.9 %, 73.2 % and 79.3 % emission reductions compared to BAU, and 60 %, 63.1 % and 71.5 % reductions with respect to road passenger transport emissions in 1990 respectively. The less impactful scenario combinations, 'A + B + C' and 'A + C + D', were predicted to achieve similar emission reductions, namely 58.6 % and 59.3 % reductions with respect to the BAU base-case and 43 % and 44 % reductions with respect to 1990 levels.

The requirement for three or more interventions to meet the emission reduction target, as illustrated by Figs. 5, 6 and 7, confirms that a single intervention is likely to be insufficient in tackling transport emissions and a broad package of interventions is needed. This corroborates the findings of previous works (Velez & Plepys, 2021; Element Energy, 2021) which emphasise the need for implementation of multiple measures to achieve effective emission reductions. In the instances where the emission reduction target is met, interventions 'B' and 'D' are the only ones to be present in each case. This indicates these interventions could have a critical role and further emphasises their particular effectiveness. Regarding interventions 'A' and 'C', their impact on emissions was projected to be less significant compared to interventions 'B' and 'D'. However, considering the prediction that at least three interventions are

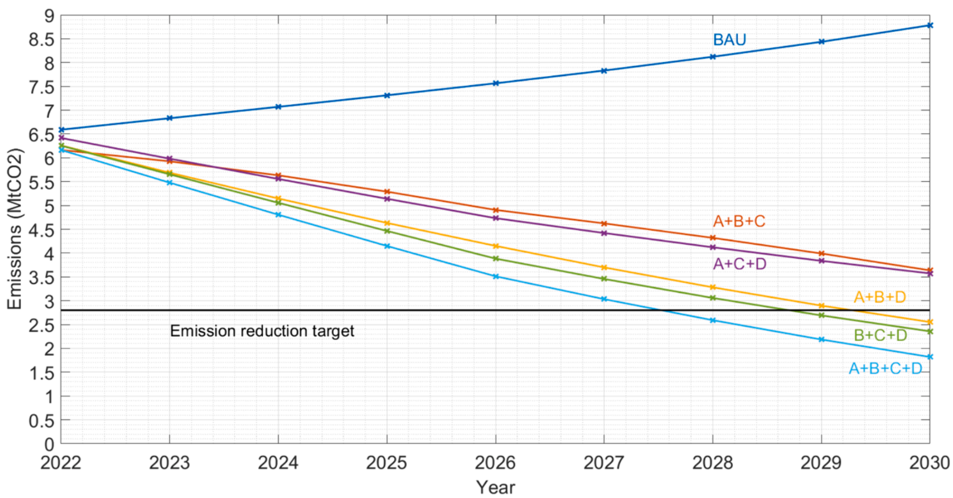

Fig. 7. Emissions trends predicted by the model under implementation of groups of three and four interventions.

necessary to meet the emission reduction target, their contribution was still found to be important.

4.4. Car kilometres travelled

The model also forecasts the car kilometres travelled in Scotland between 2022 and 2030 for each possible scenario combination. The results for the total distance travelled by car under all fifteen scenario component combinations and the BAU case are shown in Fig. 8. Some scenario combinations feature the same car kilometres travelled, primarily because intervention C does not feature any change in car kilometres, and so have been grouped accordingly.

The car kilometres travelled in each scenario set are compared to a 20 % reduction compared to 2019 levels (as mandated by the Scottish Government (Transport Scotland, 2022b), see Appendix F) and this target threshold is represented on the result plot by a black horizontal line.

Like emissions, all combinations of interventions are projected to result in a decrease in car kilometres with respect to the BAU case, but not all are predicted to give a decrease over time. Namely, scenarios 'B', 'B + C', 'B + D', 'B + C + D', 'A + B', 'A + B + C', 'A + B + D' and 'A + B + C + D' are those projected to give a decrease in car kilometres over time, and only scenarios 'B + D', 'B + C + D', 'A + B', 'A + B + C', 'A + B + D' and 'A + B + C + D' are forecasted to achieve the 20 % reduction in car kilometres. The scenarios that were predicted to achieve the target were forecast to enable reductions in car kilometres between 25 % and 42.8 % with respect to 2019 levels, and 52 % and 63.4 % with respect to BAU in 2030. The scenarios that were not projected to meet the target were predicted to facilitate a reduction in car kilometres between 13.3 % and 44.1 % compared to BAU. Comparing these scenarios to 2019 levels for car kilometres, the predicted percentage change ranged from a 35 % increase to a 12.7 % decrease in car kilometres travelled.

A combination of at least two scenario components is required to meet the car kilometre reduction target, and component 'B' is the only intervention to be present in all scenarios predicted to achieve the target. This again highlights the potential effectiveness of intervention 'B' in facilitating both emission and car kilometre reductions in line with government targets, while also emphasising the need for a comprehensive package of interventions rather than a single solution. It is notable that all scenarios predicted to achieve the emission reduction target (see Fig. 7) also meet the car kilometre reduction target (see Fig. 8). However, there are additional scenarios that meet the car kilometre reduction target while not achieving the emission reduction target. This indicates that reaching the car kilometre reduction target does not necessarily guarantee the achievement of the emission reduction target in Scotland.

Interestingly, intervention 'D', which does not explicitly target car kilometres travelled but rather the EV penetration of the vehicle fleet, was projected to achieve a similar car kilometre reduction to intervention 'A' with respect to BAU. This appears to be due to an overall decrease in car ownership in scenario 'D', with a projected 24.8 % reduction in the number of cars by 2030 compared to the BAU base-case. This, in turn, is driven by the halting of growth in the petrol/diesel car market. While this is somewhat offset in the model by the increase in EV numbers spurring further growth in the EV market, the overall number of cars remains less than that in the BAU base-case. Combined with the significant ability of scenario component 'D' to reduce transport emissions, these results suggest it is a highly impactful intervention. It should, however, be noted that other considered interventions (namely the modal shifts to active travel and bus) provide additional societal benefits in the form of enhanced public health (Woodcock, et al., 2009) and greater societal equity (Douglas, et al., 2018; Douglas, et al., 2023), which intervention 'D' does not inherently provide. These factors should also be considered when undertaking policy decision making.

4.5. Limitations

There are limitations and considerations associated with the validated system dynamics modelling framework which should be

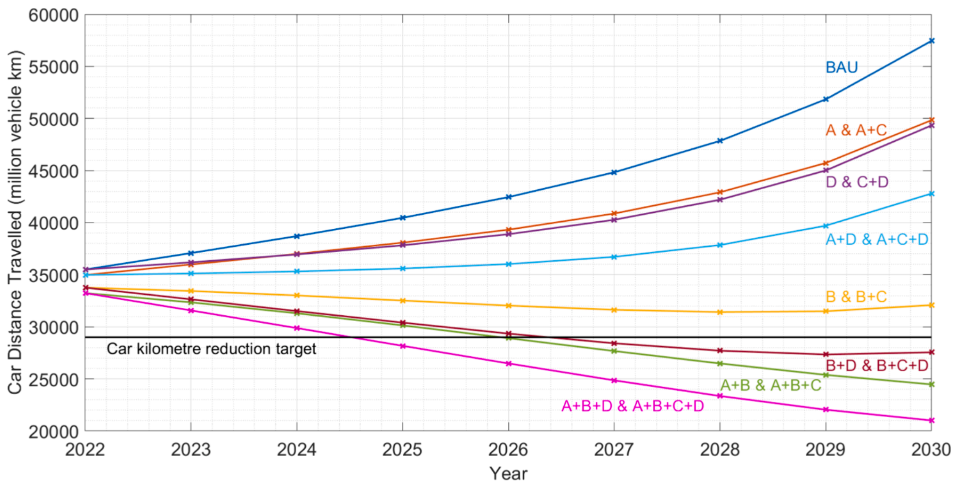

Fig. 8. Car kilometre trends predicted by the model under implementation of all possible combinations of interventions.

kept in mind when interpreting these results. These will be summarised here for clarity. First, while vans were excluded from the model, data on car and van journey distances was used to inform modal shift variables. This data was sourced from the 2021 Scottish Household Survey, featuring the latest available figures but employing a different data collection method due to the COVID-19 pandemic. A key disparity between the 2021 Scottish Household Survey and those conducted prior to the pandemic is the data sample size. However, the 2021 sample size was only 6 % smaller than the year with the smallest sample size pre-pandemic. Furthermore, when comparing the results for journey distance, the values for the 2021 Scottish Household Survey were relatively in line with pre-pandemic versions. Although historically recorded data for car distance travelled was available for Scotland, no breakdown was given for the distance travelled by petrol/diesel cars and EVs. Therefore, it was assumed that the proportion of each car type (EV and petrol/diesel cars) corresponds to their share of the total car kilometres that each car type drove. Regarding the modelled scenarios, all were informed by Scottish Government planned interventions (Transport Scotland, 2013; Transport Scotland, 2022). However, it is important to note that not all individuals may be able to complete car journeys under 10 km via active travel, as suggested by intervention 'A', particularly those individuals with mobility problems. Additionally, intervention 'C' modelled an increasing proportion of electric buses beyond 2024, aiming for full fleet electrification by 2026. Yet, practical challenges, such as battery degradation and the inability of buses to serve routes due to restricted range (Howgego, et al., 2022), could hinder this transition. Furthermore, the calculation of the emission reduction target threshold presented in this paper (see Appendix F), assumes a 56 % reduction in emissions for the transport modes included in the model (cars, buses and motorcycles). Therefore, it was assumed that these modes are expected individually to achieve a 56 % reduction (Transport Scotland, 2023c). In practice, other transport segments like air, maritime, and freight might contribute significantly to achieving the overall emission reduction target, potentially reducing the burden on the road passenger modes. Despite this, given road transport's significant contribution to overall transport emissions (Transport Scotland, 2023d), this sector will remain a key target of emission reduction efforts and equally, could play a major role in achieving the target. Future research could investigate the utility of a specific emissions target for road passenger transport and determine an appropriate threshold. The present paper does not consider how users make the mode choices that would facilitate the modal shifts considered in the modelling scenarios. Further work could consider supporting policies and actions that could influence mode choice to achieve the modal shifts.

5. Implications for policy and future work

The results of this study give insight into the impact of key interventions, namely modal shifting to more sustainable modes and electrification of bus and private car fleets, on transport emissions. The findings presented in this paper have important implications for policy, transport planning and future work. There are subsequent recommendations for critical areas where supporting policy should be focused or enhanced and for ways in which the transport system could be planned and developed in future.

The demonstrated efficacy of modal shifting of medium-length car journeys to buses and the transition to EVs suggests that these should be areas where supporting policy is targeted. Scottish Government polices supporting a shift towards EVs have been found to be relatively effective at reducing emissions (Scottish Government, Ricardo and UK Centre for Ecology and Hydrology, 2024). However, careful thought will need to be given as to how this transition can be enabled equitably while still prioritising active travel and public transport modes. Key challenges include providing equitably accessible charging infrastructure (Hardman, et al., 2021), reducing the need for car ownership and enhancing infrastructure and services for alternative modes to private cars. It is crucial to distribute public EV charging facilities spatially in a way that encourages active travel or public transport use. Selecting suitable charging infrastructure types (i.e. charging speed and power rating), particularly accounting for the ability of grid infrastructure to manage such additional loads, and setting appropriate and perhaps standardised tariffs that do not penalise those unable to charge domestically but equally do not incentivise driving further than necessary to access cheaper rates will be key considerations.

While specific existing policy packages supporting modal shifting in Scotland (e.g. investments in active travel and bus infrastructure, provision of free bus travel for certain age groups) have also been forecast to facilitate emissions reductions in Scotland (Scottish Government, Ricardo and UK Centre for Ecology and Hydrology, 2024), this study's findings suggest that further enhancing policy support for the modal shifting of medium-length car journeys to bus travel could amplify emission reduction efforts. Investing in the development of MaaS, which has been shown to effectively encourage modal shifting away from the private car and towards public transport (Zhao, et al., 2021; Labee, et al., 2022; Cisterna, et al., 2022) could be advantageous. The Scottish Government's financial support for a series of individual regional MaaS pilot schemes (Transport Scotland, 2023b) is a positive step. Investing in the development of a nationwide MaaS programme (or similar system) that interacts or integrates seamlessly with public transport provision across different regions of Scotland, or potentially other UK regions, could help promote modal shifting of medium-length and longer car journeys that may cross regional boundaries.

Furthermore, enhancing public transport provision so that it can rival the private car's sense of autonomy (Orozoco-Fontalvo & Moura, 2023) and meet the diverse needs of different groups (e.g. shift workers, those with additional care responsibilities, those who operate at multiple workplaces) who may travel at unconventional times or require unconventional routes, will be key to enabling a modal shift of medium-length car journeys. Addressing other key barriers to public transport that protected groups face (e.g. cost of transport services and experience of transport poverty (Martiskainen, et al., 2023; Sustrans, 2016), safety concerns which are disproportionately experienced by certain groups such as women (Skellington Orr, et al., 2023)) should be treated as a priority in order to encourage use of this mode, especially for longer journeys.

The important role that the modal shift to active travel and electrification of the bus fleet could play in bolstering the emission reduction impact of other interventions to enable achievement of emissions targets, indicates that policies supporting these interventions remain critical. A significant modal shift towards active travel may prompt an increase in uptake of electric micromobility modes such as electric bicycles and scooters (Christoforou, et al., 2021), which can pose their own set of challenges (Cuffe, 2018). It is crucial that active travel infrastructure is designed to safely accommodate these alongside other active travel modes.

The results of this work also indicate that the car kilometre reduction target is generally a viable strategy for reducing transport emissions, with other works highlighting a reduced car dependency can enable a more equitable transport system (Douglas, et al., 2018; Douglas, et al., 2023). However, since achieving the car kilometre reduction target alone may not ensure achievement of emission reduction targets (as discussed in Section 4.4), interventions beyond a 20 % reduction in car kilometres travelled may be required. Again, the projected efficacy of modal shifting to bus in reducing car kilometres indicates that this intervention warrants robust policy support. Additionally, the car kilometre reduction potentially facilitated by shifting to EVs suggests that policies promoting a reduction in car ownership could facilitate an effective decrease in car kilometres travelled. Such legislation could further support development of zero-emission car clubs in Scotland (Transport Scotland, 2022a), which are known to reduce personal car ownership (Rabbitt & Ghosh, 2016) and emissions (Velez & Plepys, 2021), or support MaaS initiatives as an alternative to private car use, though their impact on car ownership remains disputed (Zhao, et al., 2021; Pritchard, 2022; Orozoco-Fontalvo & Moura, 2023).

Further research work is needed to explore the relationship between car ownership and car kilometres travelled in the Scottish context for comprehensive policy recommendations to be developed. Additional research work should consider how to address issues associated with increasing EV uptake in the Scottish context and explore equitable solutions for the evolving demand for energy and charging infrastructure. It is also necessary to explore the feasibility and design of a nationwide MaaS system or multiple localised MaaS systems that are interoperable with their regional counterparts in Scotland. Furthermore, work seeking to determine the most cost-effective and efficient pathways to delivering the specific enhancements to public transport provision mentioned above (i.e. ensuring public transport can meet the diverse needs of different groups, addressing barriers to access such as safety concerns, cost etc.) is warranted. Increased active travel and electrification of the bus fleet are both interventions that will likely contribute to the decarbonisation of the road passenger transport sector, further research on their effective implementation within the Scottish context (and supportive legislation) would therefore be valuable.

Additionally, further research exploring the likelihood and extent to which the behavioural change considered in this paper (i.e. modal shifting away from the private car and transitioning towards EVs) can be achieved is warranted. Exploration of pathways to enabling these changes such as social marketing programmes and other policy packages could give insight into how these shifts can be effectively delivered. Specifically, further work should explore how mode choice can be effectively influenced by supporting policy to achieve the modal shifts considered in this paper. Facilitation of a modal shift may be more challenging during wintertime and times of poor weather (Mehdizadeh, et al., 2019). Potential seasonal impacts on the achievement of a modal shift in the Scottish context, particularly during the winter months, should also be the subject of future work. The present model could also be expanded and developed to be applicable to other important problem contexts and to give insight into other relationships and complexities in the transport sphere. For example, through addition of further variables, feedback loops and structures, the model could consider concepts such as induced demand and the impact that policy surrounding land use and space allocation given to private mobility, particularly cars, may have on modal shifting. However, such extensions would require additional data and careful model development to ensure the validity of results is not compromised and any limitations can be understood.

In summary, the substantial challenge transport emissions pose to a net zero future in Scotland, and the cumulative nature of emissions, highlight the urgency of achieving reductions soon. Understanding the likely effectiveness of planned interventions in meeting emission targets is critical. Previous studies (Velez & Plepys, 2021; Element Energy, 2021) highlight the need for multiple interventions to achieve significant emission reductions, a finding that is strongly supported by this work. The transition to EVs and the modal shifting of medium-length car journeys to bus travel were identified as the most effective interventions. While a 20 % reduction in car kilometres travelled has been found to be beneficial for lowering emissions, in isolation it may not guarantee achieving the target of a 56 % reduction in emissions.

6. Conclusion

This paper has developed, validated and applied a system dynamics model of the Scottish road passenger transport sector to explore the likely ability of planned interventions to reduce transport emissions in Scotland, in line with government targets. Specific interventions considered were the modal shifting of car journeys under 10 km to active travel; the modal shifting of car journeys between 10 and 40 km to bus transportation; achieving a 60 % electrification of the bus fleet by 2024; and a 50 % reduction in petrol/diesel cars by 2030, with these cars being replaced by EVs. The potential contribution these interventions can make towards achieving Scottish Government targets, namely a 56 % reduction in transport emissions compared to 1990 and a 20 % reduction in car kilometres compared to 2019, was explored. With the 2030 deadline for these targets rapidly approaching, it is pertinent to ensure that planned interventions are fit for purpose and effective.

Results indicated that certain combinations of interventions would be able to achieve the government mandated 56 % reduction in emissions by 2030. However, the implementation of at least three interventions was required in each case, highlighting the need for a broad programme of measures. The transition from petrol/diesel cars to EVs and the modal shifting of medium-length car journeys to buses were found to drive the most significant emissions reductions, indicating these are areas where supporting policy should likely be prioritised. Regarding car kilometres travelled, results indicated that the 20 % reduction target could also be met by 2030 through certain combinations of interventions. In each case, at least two interventions were required to meet the target, indicating that this too will require a programme of measures rather than a single solution. The modal shifting of medium-length car journeys to buses was again found to be a particularly effective intervention in terms of car kilometre reduction. Furthermore, it was found that while the 20 % reduction in car kilometres travelled can facilitate a reduction in emissions, its achievement does not guarantee also achieving the

56 % emissions reduction target.

These findings offer insight into the potential effectiveness of planned interventions to achieve meaningful emission reductions and have implications for future research, policy and transport planning. With the predicted efficacy of transitioning to EVs comes a need to ensure such a transition is enabled equitably, whilst still prioritising active travel and public transport modes. Achieving a spatial arrangement of public EV charging infrastructure that encourages use of these other modes, as well as ensuring the resultant changes in demand for energy and charging infrastructure are met equitably, presents a number of challenges and potential issues that require further work to address. Additionally, the likely effectiveness of modal shifting medium-length car journeys to buses indicates that robust policy support for enhancing attractiveness and equitable access to this mode is warranted. Addressing barriers that some groups face to public transport such as safety concerns, cost or lack of service provision were highlighted as being particularly important in this context. Prioritising the interoperability of localised MaaS schemes such that they can interact seamlessly, or aiming for a nationwide MaaS system, may also promote the switching of medium-length or longer car journeys to public transport. Further research is required to understand how travel behaviour and mode choice can effectively be influenced by supporting policies and actions to enable these modal shifts in the Scottish context. As other international governments begin to introduce car kilometre reduction targets and, more broadly, tackle transport emissions as a significant barrier to net zero, it is hoped that the modelling approach and findings of this study will also support the development and evaluation of transport policy in a broader international context.

Funding and Acknowledgements

Kathleen Davies was supported by a University of Strathclyde funded PhD studentship. Edward Hart is funded by a Brunel Fellowship from the Royal Commission for the Exhibition of 1851. This research was partly supported by Arnold Clark Automobiles Ltd.

CRediT authorship contribution statement

Kathleen Davies: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Edward Hart:** Writing – review & editing, Supervision. **Stuart Galloway:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors 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.

Appendix A

Table A.1 provides the deterministic equations for endogenous variables (according to Fig. 4). Sources are included for data used: to interrogate the nature of relationships between variables in the Scottish context and inform model structure; for regression analyses to determine equations where applicable; to validate the model.

Note that not all deterministic equations were the result of regression analysis. Equations in the socioeconomic and emissions modules (according to Fig. 3) and the 'total distance travelled' equation were informed by previous literature (Zhang, et al., 2022) and logical reasoning.

Table A1
Deterministic equations used in model, derived through regression techniques using Scottish transport and socioeconomic data, the sources of which are also provided.

Variable (units)	Deterministic Equation	Source
Changes in population (people)	Population × (population raw growth rate + 0.02 × GDP growth rate)	(Zhang, et al., 2022)
GDP growth rate (dimensionless)	raw GDP growth rate + 0.01 × population raw growth rate	(Zhang, et al., 2022)
Changes in GDP (£million)	GDP × GDP growth rate	(Zhang, et al., 2022)
GDP per capita (GBP, £)	(GDP × 1000000)/Population	(Zhang, et al., 2022)
Changes in number of motorcycles (vehicles)	(−0.01966597396) × Population + 2.244465309 × GDP per capita + 0.314697936 × Road network + 21847.70266	(Office for National Statistics, 2022; Office for National Statistics, 2023; Transport Scotland, 2022d)

(continued on next page)

Table A1 (*continued*)

Variable (units)	Deterministic Equation	Source
Changes in number of petrol/ diesel cars (vehicles)	Population × (−0.2197432104) + GDP per capita × 21.86963814 − Road network × 4.741946148 + 830053.8732 + petrol/diesel car shift	(Office for National Statistics, 2022; Office for National Statistics, 2023; Transport Scotland, 2022d)
Changes in number of electric vehicles (vehicles)	EXP(−97.493) × EXP(Population × (−4.6103E-07)) × EXP(GDP per capita × 0.00039271) × EXP(Road network × 0.0016843) + electric vehicle shift	(Office for National Statistics, 2022; Office for National Statistics, 2023; Transport Scotland, 2022d)
Changes in road network (km)	0.001637 × GDP − 139.271	(Office for National Statistics, 2023; Transport Scotland, 2023d)
Distance travelled by motorcycles (km)	IFTHENELSE(Number of motorcycles>=0, Population × (−70.1756) + Number of motorcycles × 2749.243 + 4.7E + 08, 0)	(Office for National Statistics, 2022; Transport Scotland, 2023d; UK Government, 2022)
Distance travelled by petrol/ diesel cars (km)	IFTHENELSE(Number of petrol/diesel cars>=0, (Number of petrol/diesel cars × 11390.44997 + Population × 2453.347274 + (−5566156817)) × (1 − (active travel modal shift + bus modal shift)), 0)	(Office for National Statistics, 2022; Transport Scotland, 2023d; UK Government, 2022)
Distance travelled by electric vehicles (km)	IFTHENELSE(Number of electric vehicles>=0,(14444.19276 × Number of electric vehicles + 2.748522506 × Population + (−14560376.24)) × (1 − (active travel modal shift + bus modal shift)), 0)	(Office for National Statistics, 2022; Transport Scotland, 2023d; UK Government, 2022)
CO_2 emissions from motorcycles ($kgCO_2$)	carbon emission factor motorcycle × distance travelled by motorcycles	(Zhang, et al., 2022)
CO_2 emissions from petrol/ diesel cars ($kgCO_2$)	carbon emission factor petrol/diesel car × distance travelled by petrol/diesel cars	(Zhang, et al., 2022)
CO_2 emissions from electric vehicles ($kgCO_2$)	distance travelled by electric vehicles × carbon emission factor EV	(Zhang, et al., 2022)
CO_2 emissions from buses ($kgCO_2$)	(carbon emission factor bus × distance travelled by buses × (1-proportion of electric buses)) + (proportion of electric buses × carbon emission factor electric bus × distance travelled by buses)	(Zhang, et al., 2022)
Total CO_2 emissions ($kgCO_2$)	CO_2 emissions from petrol/diesel cars + CO_2 emissions from motorcycles + CO_2 emissions from electric vehicles + CO_2 emissions from buses	(Zhang, et al., 2022)
Total distance travelled (km)	distance travelled by buses + distance travelled by electric vehicles + distance travelled by petrol/diesel cars + distance travelled by motorcycles	(Zhang, et al., 2022)

Appendix B

Table B.1 details the initial conditions of the stock variables (according to Fig. 3) alongside relevant data sources, for both the validation simulation (i.e. 2010 value) and the BAU and scenarios simulations (i.e. 2022 value).

Table B1
Stock variable initial values for both validation and scenario simulations.

Variable (units)	Validation Simulation Initial Condition	BAU/Scenarios Simulations Initial Condition	Source
Population (people)	5,262,200	5,436,600	(National Records of Scotland, 2023; Office for National Statistics, 2022)
GDP (£million)	145,051	187,300	(Office for National Statistics, 2023; Scottish Government, 2023b)
Number of motorcycles (vehicles)	68,625	76,800	(UK Government, 2022)
Number of petrol/diesel cars (vehicles)	2,254,538	2,385,800	(UK Government, 2022)
Number of electric vehicles (vehicles)	33	38,512	(UK Government, 2022)
Road network (km)	55,626	57,077	(Transport Scotland, 2023d)

Appendix C

Table C.1 provides the exogenous variable (according to Fig. 4) inputs alongside relevant data sources, for both the validation simulation and BAU and scenarios simulations, where applicable.

Note that for the 'distance travelled by buses', the value excluded from the parenthesis is the average bus vehicle kilometres travelled for the period 2010 to 2019 (Transport Scotland, 2023d), while the expression in parenthesis which adds the modal shifted vehicle kilometres is divided by the average bus capacity in Scotland (Howgego, et al., 2022) to approximate the resultant bus vehicle kilometres to be added.

Table C1
Exogenous variable inputs for both validation and scenario simulations.

Variable (units)	Validation Simulation Input	BAU/Scenarios Simulations Input	Source
Population raw growth rate (dimensionless)	(Time, {{2010.0,0.007164304}, {2011.0,0.002584954}, {2012.0,0.002653568}, {2013.0,0.003735195}, {2014.0,0.004749794}, {2015.0,0.00589987}, {2016.0,0.003718985}, {2017.0,0.002451703}, {2018.0,0.004633971}, {2019.0,4.94207E-4}})	(Time, {{2022.0,2.6E-4}, {2023.0,5.7E-4}, {2024.0,5.0E-4}, {2025.0,4.0E-4}, {2026.0,3.4E-4}, {2027.0,2.8E-4}, {2028.0,1.3E-4}, {2029.0,4.0E-5}, {2030.0, −2.2E-4}})	(Office for National Statistics, 2022; National Records of Scotland, 2022)
GDP raw growth rate (dimensionless)	(Time, {{2010.0,0.022}, {2011.0,0.023}, {2012.0,0.013}, {2013.0,0.025}, {2014.0,0.031}, {2015.0,0.011}, {2016.0,0.003}, {2017.0,0.027}, {2018.0,0.004}, {2019.0,0.011}})	(Time, {{2022.0, −0.001}, {2023.0,0.004}, {2024.0,0.008}, {2025.0,0.011}, {2026.0,0.013}, {2027.0,0.013}, {2028.0,0.014}, {2029.0,0.015}, {2030.0,0.015}})	(Office for National Statistics, 2023; Scottish Fiscal Commission, 2023)
Distance travelled by buses (km)	340,000,000 + ((bus modal shift × car distancetravelled)/36)	340,000,000 + ((bus modal shift × car distance travelled)/36)	(Howgego et al., 2022; Transport Scotland, 2023d)
Motorcycle carbon emission factor ($kgCO_2$/km)	0.11367	0.11367	(UK Government, 2023)
Petrol/diesel car carbon emission factor ($kgCO_2$/km)	0.1748	0.1748	(UK Government, 2023)
Electric vehicle carbon emission factor ($kgCO_2$/km)	0.00981765	0.00981765	(Electric Vehicle Database, 2023; Scottish Government, 2023a)
Bus carbon emission factor ($kgCO_2$/km)	1.3	1.3	(Goodall, 2007)
Electric bus carbon emission factor ($kgCO_2$/km)	0.07375	0.07375	(Scottish Government, 2023a; United States Department of Transportation, 2018)

Appendix D

The Scottish Household Survey (Transport Scotland, 2023e) provides data on the mean journey distance and statistical distribution of results by mode. Data (displayed in Table D.1) for journeys conducted by car or van as a driver was used to approximate the proportion of total kilometres travelled for journeys under 10 km and between 10 km and 40 km by car, as follows.

Table D1
Data from (Transport Scotland, 2023e) on average journey distance by mode.

Statistic	Journey distance by car/van as a driver (km)
Lower decile	1.3
Lower quartile	2.6
Median	6.6
Upper quartile	17.3
Upper decile	36.1
Mean	16.7

First, we assume that a more complete version of the dataset is available (i.e. we assume the distance of every journey taken by car/van as a driver is known). For the sake of simplicity, we further assume the data is discretised such that all journeys fall into distinct distance bins, and where the number of journeys in each bin is known. Let the journey distances be denoted $D_1, \cdots, D_M$, and the number of journeys in each bin be denoted $N_1, \cdots, N_M$, where M is the total number of distance bins. The total distance travelled by all vehicles is then,

$$D_{tot} = \sum_{i=1}^{M} N_i D_i \tag{D.1}$$

and the total number of journeys is,

$$N = \sum_{i=1}^{M} N_i \tag{D.2}$$

Therefore, the distance travelled for journeys longer than those in the j^{th} bin is,

$$D_{\geq D_j} = D_{tot} - \sum_{i=1}^{j} N_i D_i. \tag{D.3}$$

Expressing each N_i as a proportion of the total number of journeys,

$$\varphi_i := \frac{N_i}{N} \Rightarrow N_i = N\varphi_i \tag{D.4}$$

and substituting into (D.3),

$$D_{\geq D_j} = D_{tot} - N \sum_{i=1}^{j} \varphi_i D_i \tag{D.5}$$

Now, note that N is not explicitly given in the available data. However, it may still be determined. If μ denotes the mean length of a single journey then, by definition,

$$\mu = \frac{D_{tot}}{N} \Rightarrow N = \frac{D_{tot}}{\mu} \tag{D.6}$$

Substituting into the above we obtain,

$$D_{\geq D_j} = D_{tot} - \frac{D_{tot}}{\mu} \sum_{i=1}^{j} \varphi_i D_i \tag{D.7}$$

$$\Rightarrow D_{\geq D_j} = D_{tot} \left(1 - \frac{1}{\mu} \sum_{i=1}^{j} \varphi_i D_i \right). \tag{D.8}$$

The proportion of journeys greater than D_j is therefore,

$$1 - \frac{1}{\mu} \sum_{i=1}^{j} \varphi_i D_i \tag{D.9}$$

hence, the proportion of journeys less than D_j is

$\varphi_{\leq j} = \frac{1}{\mu}\sum_{i=1}^{j}\varphi_i D_i$, (D.10).

And the proportion of journeys between D_j and D_k is $\varphi_{\leq k} - \varphi_{\leq j}$. (D.11).

These quantities may now be resolved, since μ is provided directly by the Scottish Household Survey data, and $\sum_{i=1}^{j}\varphi_i D_i$ terms are readily found by interpolation of the distribution described by the Scottish Household Survey report (Transport Scotland, 2023e). In this analysis, logarithmic interpolation and discretisation into distance bins of 0.1 km was utilised. The proportion of journeys made by car or van as a driver under 10 km was found to be 0.1325, and between 10 km and 40 km was found to be 0.4414.

Appendix E

Table E.1 details the scenario variable inputs. Note that when scenario component D is being simulated, the model equation for the 'Number of petrol/diesel cars' variable must be zeroed.

Table E1
Inputs for scenario variables.

Scenario Variable	Input
Active travel modal shift	(Time, {{2022.0, 0.014724125}, {2023.0, 0.02944825}, {2024.0, 0.044172375}, {2025.0, 0.0588965}, {2026.0, 0.073620625}, {2027.0, 0.08834475}, {2028.0, 0.103068875}, {2029.0, 0.117793}, {2030.0, 0.132517125}})
Bus modal shift	(Time, {{2022.0, 0.049048778}, {2023.0, 0.098097556}, {2024.0, 0.147146333}, {2025.0, 0.196195111}, {2026.0, 0.245243889}, {2027.0, 0.294292667}, {2028.0, 0.343341444}, {2029.0, 0.392390222}, {2030.0, 0.441439}})
Proportion of electric buses	(Time, {{2022.0, 0.2}, {2023.0, 0.4}, {2024.0, 0.6}, {2025.0, 0.8}, {2026.0, 1}, {2027.0, 1}, {2028.0, 1}, {2029.0, 1}, {2030.0, 1}})
Electric vehicle shift	(Time, {{2022.0, 149112.5}, {2023.0, 149112.5}, {2024.0, 149112.5}, {2025.0, 149112.5}, {2026.0, 149112.5}, {2027.0, 149112.5}, {2028.0, 149112.5}, {2029.0, 149112.5}, {2030.0, 149112.5}})
Petrol/diesel car shift	(Time, {{2022.0, −149112.5}, {2023.0, −149112.5}, {2024.0, −149112.5}, {2025.0, −149112.5}, {2026.0, −149112.5}, {2027.0, −149112.5}, {2028.0, −149112.5}, {2029.0, −149112.5}, {2030.0, −149112.5}})

Appendix F

The Scottish Government car kilometre reduction target specifies a 20 % reduction in car kilometres travelled should be achieved by 2030, comparative to 2019 levels (Transport Scotland, 2022b). Therefore, Equation (F.1) (where T_d is the targeted car distance travelled by 2030, d_{2019} is the car distance travelled in 2019, and t_{red} is the targeted reduction factor (i.e. 20 % or 0.2)) was used to determine the targeted value for car kilometres travelled in line with the 20 % reduction, with the reported value of 36747000000 km for car kilometres travelled in Scotland, 2019 (Transport Scotland, 2023d).

$$T_d = d_{2019} \times (1 - t_{red}) \tag{F.1}$$

The Scottish Government transport-specific emission reduction targets specifies a 56 % reduction in emissions by 2030, comparative to 1990 levels (Transport Scotland, 2023c). The total reported emissions of transport in 1990 was 9.2 Megatonnes of CO_2 ($MtCO_2$) (Transport Scotland, 2020a). Table F.1 details the contribution of the modes included in the model to the overall transport emissions in 1990 (Transport Scotland, 2020a).

Table F1
Data from (Transport Scotland, 2020a) on the contribution of modes included in the model to transport emissions in 1990.

Mode	Contribution to overall transport emissions
Cars	63 %
Motorcycles	6 %
Buses	0.4 %
Total	**69.4 %**

The emissions of the modes included in the model in 1990 were therefore calculated using Equation (F.2), where E_{m1990} is the emissions of modes included in the model in 1990, and $E_{tot1990}$ is the total transport emissions in 1990.

$$E_{m_{1990}} = E_{tot_{1990}} \times 0.694 \tag{F.2}$$

The targeted value of emissions of modes included in the model in line with the 56 % reduction was then calculated using Equation (F.3), Where T_e is the targeted value for emissions by 2030.

$$T_e = E_{m_{1990}} \times 0.56 \tag{F.3}$$

The values found for targeted car distance travelled and targeted emissions were 29397.6 million km and 2.81 $MtCO_2$ respectively. These values are represented on Fig. 8 and Figs. 5, 6 and 7 by the black horizontal line labelled 'car kilometre reduction target' and 'emission reduction target' respectively.

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