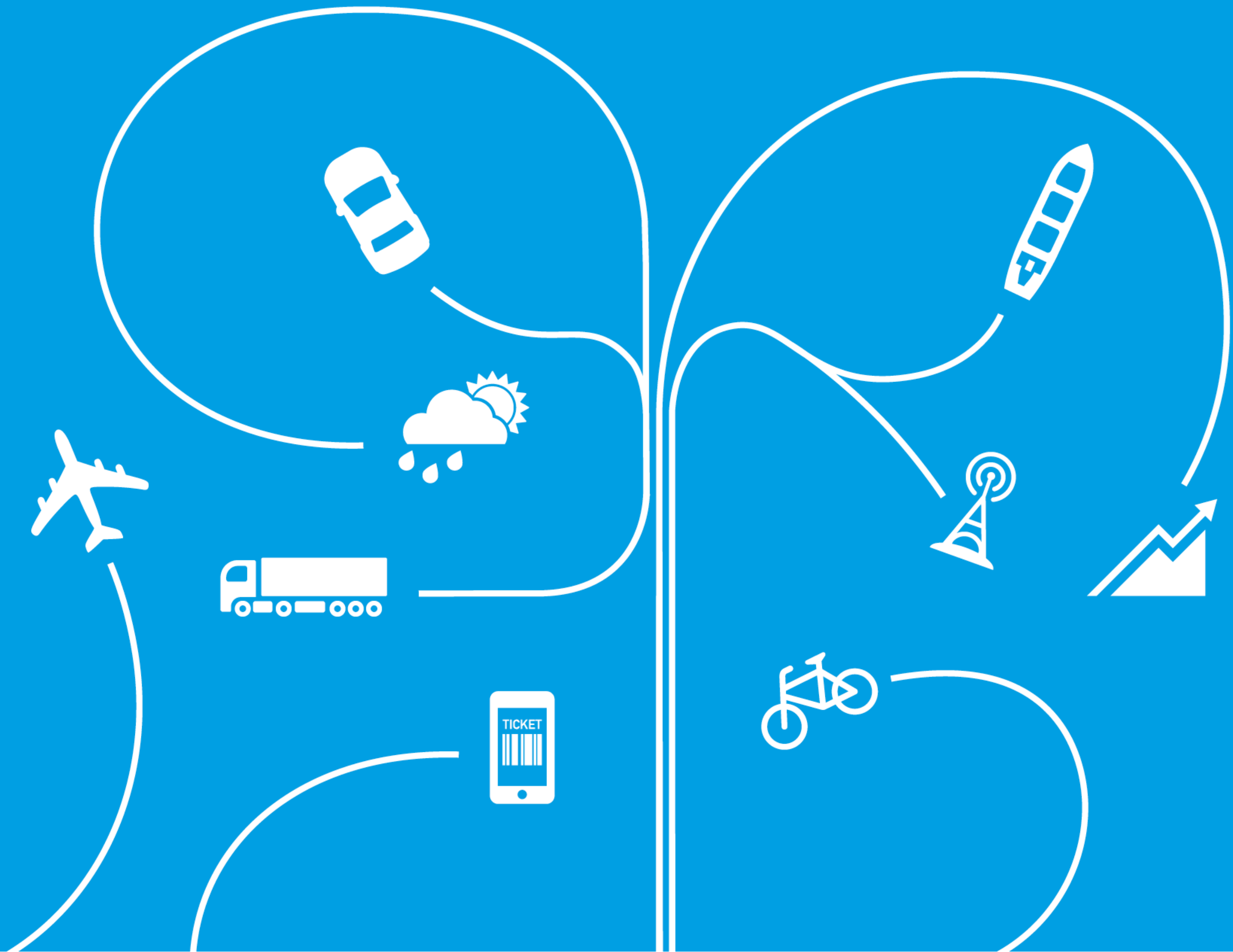
EXPLORING INTELLIGENT MOBILITY

CATAPULT Transport Systems

Effect of Connected and Automated Vehicles on Energy Usage and Emissions

System Dynamics Modelling

March 2016



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Acronyms

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
AEB	Autonomous Emergency Braking
AV	Automated Vehicle
BEV	Battery Electric Vehicle
CAV	Connected and Automated Vehicle
DDM	Driver Distraction Monitoring
DECC	Department of Energy and Climate Change
DfT	Department for Transport
DVLA	Driver and Vehicle Licensing Agency
EV	Electric Vehicle
FCW	Forward Collision Warning
FOI	Freedom of Information
ICE	Internal Combustion Engine
LDW	Lane Departure Warning
LKA	Lane Keep Assist
MaaS	Mobility as a Service
mtoe	million tonnes of oil equivalent
NTM	National Traffic Model
NTS	National Travel Survey
ONS	Office for National Statistics
PHEV	Plugin Hybrid Vehicles
TfL	Transport for London
TSC	Transport Systems Catapult
ULEV	Ultra-Low Emission Vehicles

1 Introduction

1.1 Overview

This document has been prepared by Transport Systems Catapult (TSC) for the Department for Transport (DfT). This report, along with the System Dynamics model produced on behalf of the DfT, form the deliverables for the DfT sponsored project 'Effect of Connected and Automated Vehicles on Energy Usage and Emissions' produced under the TSC/DfT MOU 2015/16. This element of the project builds upon the work undertaken in the earlier phases of the project namely the literature review and stakeholder engagement.

1.2 Background

The 2008 Climate Change Act established the world's first legally binding climate change target. The UK Government aims to reduce the UK's greenhouse gas emissions by at least 80% (from the 1990 baseline) by 2050. Reducing transport-related energy consumption has a substantial role to play in meeting these targets. A 2014 report by the Department of Energy and Climate Change (DECC) estimated the proportion of energy used by the transport sector as a proportion of total UK energy consumption to be 18% (with road transport usage being 74% of that amount at 40 million tonnes of oil equivalent (mtoe)).

Transport-related energy consumption has levelled over the last decade due to fewer domestic miles driven and more efficient propulsion technology in cars. Emerging autonomy and connectivity trends in road-transport will shortly start to influence this consumption rate, so a better understanding of the factors involved will allow increased support to be directed to those technologies, regulation or social concepts that contribute the most favourably to reducing consumption. Air quality from vehicular emissions also has the potential to be significantly affected positively or negatively by the emerging autonomy and connectivity trends.

Automated, connected vehicles and innovative personal transport systems can affect energy consumption at an individual vehicle level, at the network level and at the wider vehicle ownership / usage level. One single technology could have a favourable effect at one level and an adverse effect at another.

In addition to potential changes in transport energy consumption, there will be changes in the energy mix and point of consumption. The recent House of Commons select committee report, 'Motoring of the future', reported: "There is a general lack of knowledge in the transport sector regarding the lifecycle emissions of different technologies when design, production, use and disposal are taken into account".

This project and its system dynamics model will aid understanding of the effects of some of these new technologies. For example, the link between Automated Vehicles (AVs) and increased uptake in Electric Vehicles (EVs) often leads to predictions of potential improvements in CO_2 emissions and air quality from the use of automated systems. Coupled with this change in energy consumption, these trends are likely to cause changes in air pollutant patterns and levels (harmful gases such as NO_x, and particulates). The systems model produced under this project will also be able to investigate how, at a relationship level, the combination of increasing connectivity, automation and EV trends may effect this pattern and others like it.

1.3 Aim

The aim of the modelling aspect of this project is to better understand the relationships between factors affected by Connected and Automated Vehicle (CAV) technologies and affecting energy consumption and emissions in road transport. A number of scenarios have been considered in order to show possible outcomes which may occur or emerge from the various interdependencies.

1.4 Scope

The modelling exercise requires a tight definition of scope to indicate what is and what is not being considered. The initial scope highlighted in the Literature Review covers five levels of factors as set out in Figure 1 below.

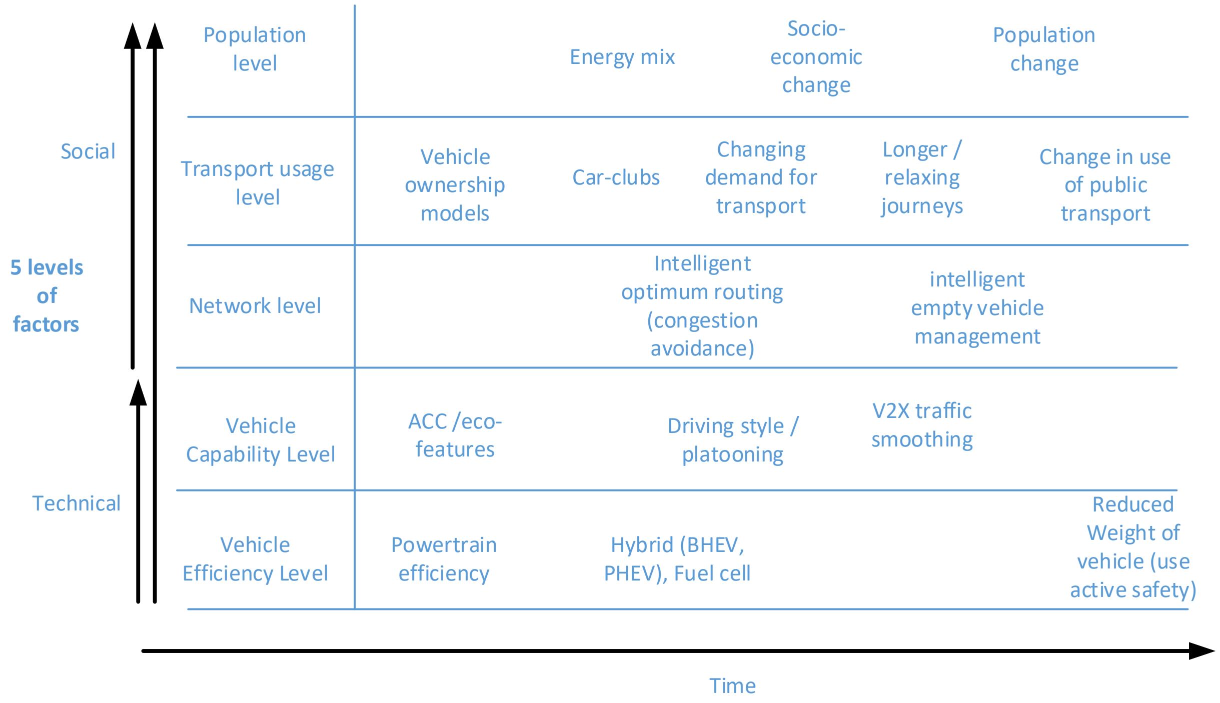


Figure 1: Five levels of factor defining the model scope

All five levels of factors have been considered in the modelling exercise to varying levels of detail. In particular, the key points regarding the model's scope are set out below:

- Geographical area: UK;
- Considering road transport, and specifically passenger cars only;
    - Freight or public transport not considered;
- Transportation modal shift not under consideration (e.g. decision to travel by train rather than car for certain journeys).

2 Methodology

2.1 System Dynamics Modelling

The transport system, including the infrastructure, supporting technology and people's usage of it is a highly complex system to understand in its entirety, with all of its trends and influences. This presents a formidable challenge to try to model the transport system to any meaningful level of predictive accuracy. There are several potential approaches to modelling such a system, including: Discrete Event Simulation, Agent Based Modelling and System Dynamics. Agent Based Modelling is a powerful technique and conceivably could be applied to try to model all of the individuals in a population making their journeys and then allowing the individual choices of each member of the population to result in emergent behaviours which can be observed at what is referred to as the macro-level. However, when looking at country-wide systems the population size is so large and the influences on each of the individuals are intricate and vary greatly that this approach would be unwieldy and impractical for the emphasis required in this work. The more naturally applicable approach is to use System Dynamics Modelling.

System Dynamics is an approach to understanding the nonlinear behaviour of complex systems over time. System Dynamics models use differential equations represented by stocks and flows, internal feedback loops and time delays to represent the system of interest. The model itself can be created in a visual manner which aids understanding, and there exists software tools which facilitate this. The key points to note are that:

- It requires a level of generalisation of the population into one or more groups with their own similar behaviours.
- A priori understanding of the relationships and behaviours is needed, or at least it must be assumed.
- The model structure is essentially static as it does not change as the model runs, although it is possible to change between fixed static structures based upon runtime conditions.

These points could be seen as a criticism and indeed they are a limitation of this modelling technique since the technological changes which are foreseen in the near future are themselves very uncertain at the current time, and the response to them by the travelling population and its governance is even less certain and difficult to predict. However, it is felt that this approach is still the right one, but instead of it being used to forecast absolute outcomes, it must instead be used to explore the plausibility of scenarios and to test assumptions against each other. This in turn can be used to focus further research attention and explore directions with governance policy and regulation.

More generally, System Dynamics Modelling can help with framing, understanding, and discussing complex issues which occur at the societal level. It has therefore been chosen for this project to support the understanding of the complex interactions between CAV technologies and transport energy and emissions.

2.2 Software Tool

Before starting the modelling exercise, the TSC considered which tool would be most appropriate for the task. The options considered are discussed below.

- **Simantics System Dynamics** is a free to use software package based upon the open-source Eclipse software development platform. This package seemed to be an ideal choice since it has an up-to-date interface and would assist with dissemination efforts having no purchase cost. Unfortunately, during trialling of this software it was found to be unstable and prone to regular random crashes which made it unusable in the timeframe of this work.

- **Mathworks Matlab with SIMULINK** could also have been adopted. However, the SIMULINK interface serves a wide variety of modelling and model based software generation purposes which does not lend itself as well to visualising System Dynamics Models as dedicated packages do. Since for this the model itself is as important as its output for describing the problem space, it was felt that it would be better to use a dedicated package.

- **Vensim from Ventana Systems and Stella Professional/iThink** from Isee Systems are both similar and well respected packages for System Dynamics modelling. Stella and iThink are essentially the same package, but iThink has been adapted to be more suitable for business and finance modelling.

The decision was made to use Stella Professional from Isee Systems. It was chosen over Venisim as it appears to have a more up-to-date interface and has a number of mechanisms to allow end-users to run models that have been created. The models can be run both with and without the need for a fully functional licenced version of Stella installed, such as a standalone player application and a licenced runtime which allows the user to change more of the model.

2.3 Model Structure

Based on the literature review undertaken earlier in the project, a number of areas were identified which should be included in the model. These included any aspects of road transport which affect energy consumption or emissions and which could be influenced by CAV technology. Many of these interactions were represented in the relationship map shown in Figure 2 below.

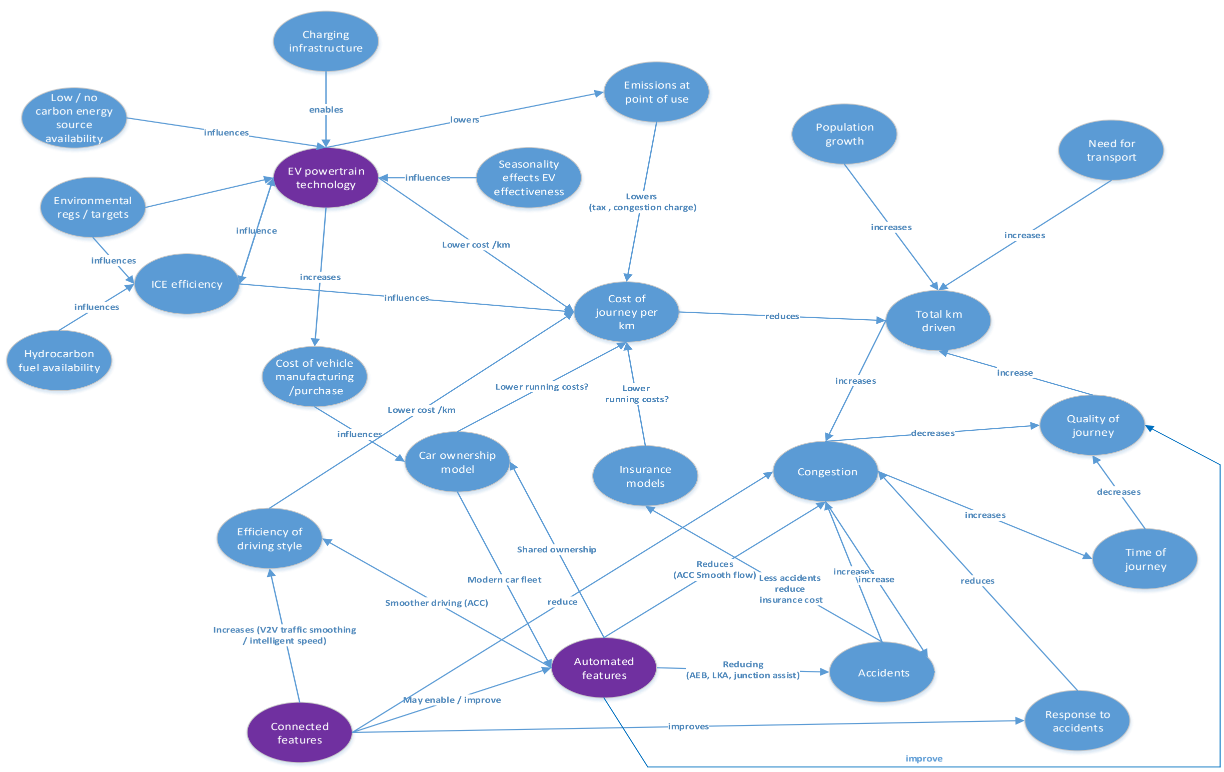


Figure 2: Initial relationship map developed during Literature Review phase of project

In order to provide a clear structure for the System Dynamics model, these aspects were categorised into six main areas, which would form the top level modules under which the model structure would be developed further.

These areas are:

- CAV Technology;
- Powertrain Technology;
- Infrastructure;
- Journey Characteristics;
- Vehicle Ownership;
- Population.

The final high level module in the model is “Energy Emissions” which computes the output in terms of energy and emissions based on all the other parts of the model. The top level structure of the model can be seen in Figure 3 below.

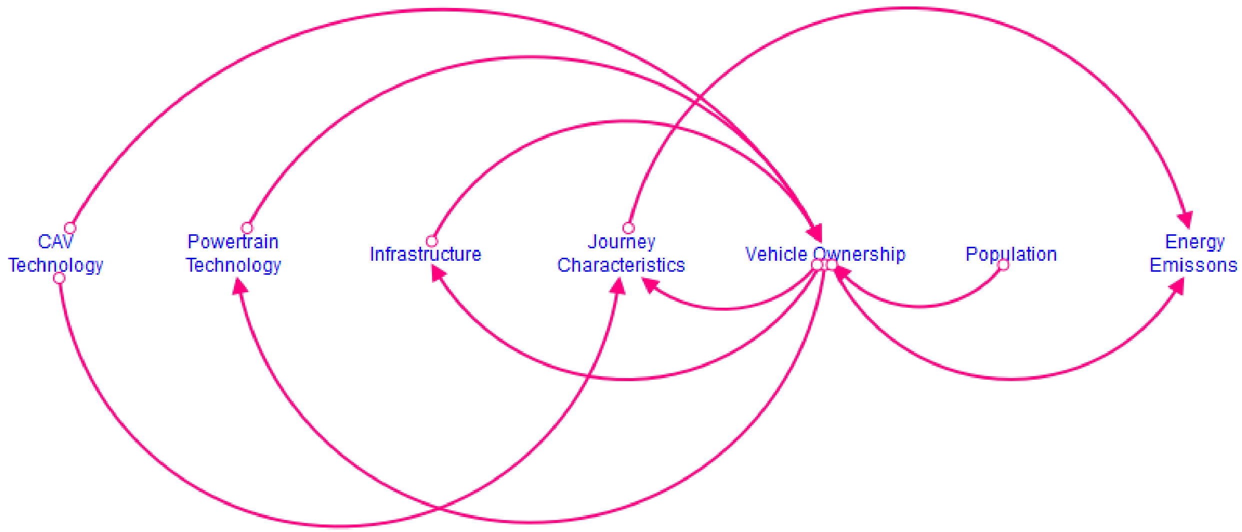


Figure 3: Top level model structure

Due to the nature of the modelling approach and software chosen, there is no clear separation between the “basic” model and “future” model described in the project proposal. The model has been setup to run over time from 2015 to 2035, initialised with current data where this is available and sensible estimations where it is not. The model can be updated with more correct data as it becomes available either through research or mining of existing data sources. The model can be set to run over a wider time span, but many of the relationship curves may not hold to sensible estimates if the model is advanced much further into the future beyond the 2035-time frame.

2.4 Data Management

The Stella software provides a mechanism to import data constants and initial values for stocks[1] from MS excel spreadsheets. For use with the model a data dictionary spreadsheet has been created and organised into worksheets for each of the seven top level modules. This provides a single place to edit the values of constants used as parameters within the model without needing to manually explore the whole model structure to find and set values. It also provides an opportunity to create different spreadsheets to explore different scenarios by changing parameters such as feature adoption rates and influences.

2.5 Module Descriptions

The model modules are described below. Assumptions specific to each module are listed in the relevant sections.

[1] In terms of a metaphor, a stock can be thought of as a bathtub in terms of dynamics modelling.

2.5.1 CAV Technology

This module covers CAV technology. The area has been broken down into three sections: Connectivity, Advanced Driver Assistance Systems (ADAS) and High Automation.

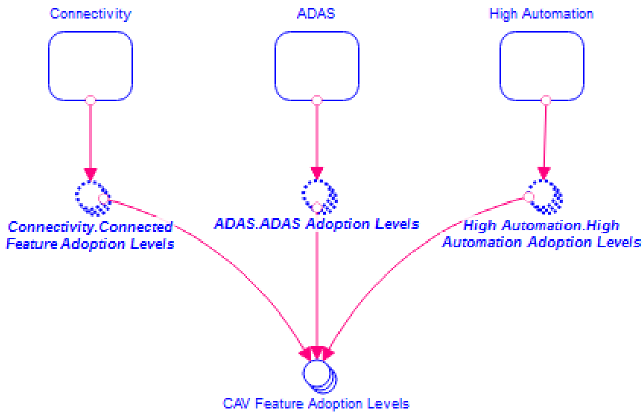


Figure 4: CAV Technology module structure

The Connectivity sub-module includes features such as Connected Parking, Connected Hazard Warning and Connected Forward Collision Warning. In future, other connected features could be added, such as Eco-navigation, Connected Speed Control and Proactive Energy Management (e.g. cylinder deactivation, diesel regen scheduling, and hybrid powertrain management) based upon the dynamically predicted journey length and progression. Each connected feature's uptake rate and the feature's potential effects are modelled within the Connectivity sub-module.

The automation part of the CAV module is broken down into two: ADAS and High Automation. Based on the SAE levels of driving automation described in Figure 5, ADAS is considered to cover levels 1 and 2, and High Automation levels 4 and 5. The distinction is made at this point as levels 1 and 2 (ADAS) require the human driver to still be monitoring the driving environment at all times, whereas for levels 4 and 5 (High Automation) the human driver is able to disengage from the driving task for all or part of the journey. This difference affects how uptake of the features might influence the transport system. For ADAS features, the main mechanism is through improved safety and potentially smoother traffic flow and driving style changes. High Automation features, however, could have more profound influences on how people travel and how they own or use vehicles and transport services, and even drastically change vehicle ownership models.

The ADAS sub-module includes features such as Driver Distraction Monitoring (DDM), Lane Departure Warning (LDW) and Lane Keep Assist (LKA), Forward Collision Warning (FCW) and Autonomous Emergency Braking (AEB). In future, other ADAS features could be added such as Adaptive Cruise Control (ACC).

For the purposes of the model and this report, two levels of high automation have been defined. The first is Highway Pilot which is already tentatively starting to enter the market place. We define Highway Pilot as being where the automation system is entirely in control of the vehicle when it is travelling on a highway (dual carriageway or motorway). This would enable a human driver to use the time on the highway for other activities, but may still require a certain level of supervision, or the ability to resume control at relatively short notice. A qualified driver would still need to be in attendance at the driver's seat at all times, so sleeping or working in the rear of the vehicle would be precluded. However, the model has been used to postulate that the lower workload and the ability to read (for instance) while the vehicle is being driven under software control, could make longer commutes more acceptable to more people, due to the lower concentration and fatigue levels and the reduced loss of productive time in their day. It may also make them more likely to choose the use of their own vehicles over transit transport for the occasional longer distance journeys.

The second level of high automation we have termed Autopilot. This covers the eventuality that vehicles will be able to perform end-to-end journeys in a fully automated and unsupervised fashion. They would not require a qualified driver to be present in the vehicle and would open up both the prospect of Mobility as a Service (MaaS) and the use of vehicles by current non-drivers. This could affect people who are below the current minimum driving age, older people and those with disabilities currently preventing them from driving.

Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)
Human driver **monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
Automated driving system **("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 5: Summary of Levels of Driving Automation for On-Road Vehicles, from http://cyberlaw.stanford.edu/loda

The potential relationships described here have been included within the model. Outputs from the CAV technology module are used to influence elements of the journey characteristics and vehicle ownership modules.

For most of the features a standard adoption model has been used. The feature performance is normalised between 0 and 1 and is assumed to improve from some baseline level towards 1 over time at a rate determined by the improvement factor. The adoption level also changes with time between 0 and 1, once the roll-out year has been reached, but the adoption rate or 'uptake rate' increases as a function of:

- Current adoption level;
- Current performance level scaled by its level of influence for that feature;
- Overall adoption factor.

The resultant uptake value is used to control the proportion of *new* vehicles which have the feature in question fitted, not the overall proportion of the vehicle parc which have the feature (i.e. there is to be no feature retrofitting to existing vehicles). A typical adoption model is shown in Figure 6. There is a potential feedback loop which has been purposefully omitted since the relationship is not clear. If a feature is selling well then a vehicle manufacturer may opt to leave it alone, or reinvest into it to keep it current and competitive. If a feature is not selling well they may also leave it alone assuming there is no demand for it, or they may attempt to invest in it through further development to encourage its uptake. As it is not clear how this may evolve for a particular feature there is no feedback from feature uptake to feature performance.

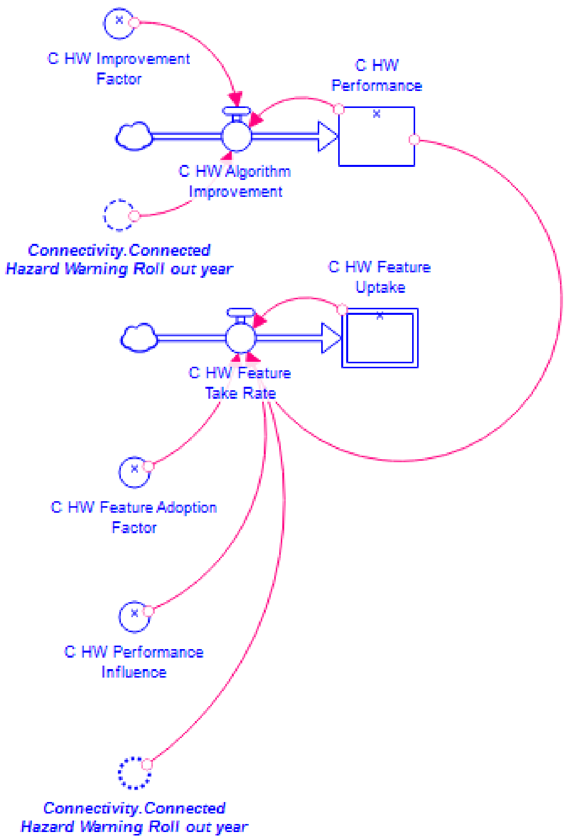


Figure 6: Typical Feature Performance and Adoption Model Section

Performance and adoption curves are shown in a plot in Figure 7 below.

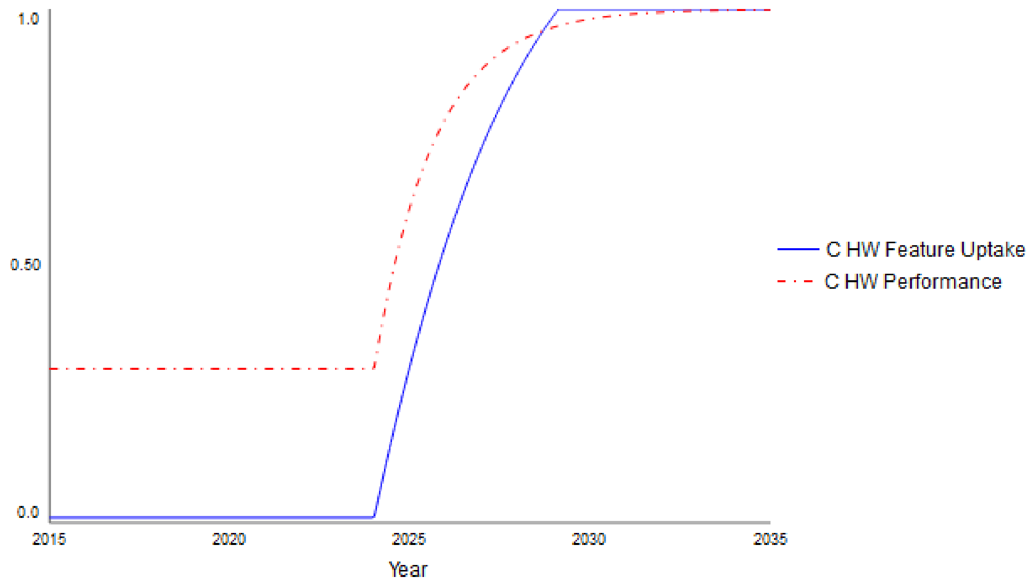


Figure 7: Typical Feature Performance and Adoption Curves

The following assumptions have been made:

- No retrofitting of features to existing vehicles in the parc except for connected parking which could be implemented from mobile devices without a connection to the vehicle.
- A more conventional early-adopters and influencers model has not been used since the peer influence relationship is not as clear for automotive features as for something more prominent and with a shorter life-cycle, such as smartphones.

2.5.2 Powertrain Technology

Figure 8: Powertrain Technology module structure

The Powertrain Technology module aims to model trends in vehicle powertrains (Internal Combustion Engine (ICE), hybrid, electric etc.) which will affect the types of vehicles that are on the road and therefore consuming energy and producing emissions. The current focus of the model is on battery technology as this has a significant effect on the uptake of battery electric and hybrid vehicles, which in turn can have a dramatic effect on the energy and emissions of the overall parc. In addition, it is thought that fully EVs are a natural counterpart to vehicle automation, particularly for 'last-mile' and shorter journeys. An increase to power density and specific capacity, and charging rates of batteries is a natural enabler for EV uptake and the viability for their use in MaaS and a wider range of journeys. Changing the assumptions of how battery technology may evolve significantly changes the predictions for energy and emissions and therefore it has to be considered together with the adoption of other technologies, rather than being decoupled as a separate discipline. Battery performance also impacts upon the overall energy picture as well as affecting the uptake and viability of BEVs in general. Usage behaviours impact upon battery performance both in terms over capacity loss and charging efficiency. The so-called charge acceptance of a battery depends heavily on its current state of charge. For example, batteries which are kept nearly fully charged and used for short journeys between charges will have a poor charge acceptance, losing more of the charging power as heat. As with other parts of the model, the system dynamics approach dictates that averages are used. With the Battery Technology sub-module, individual journeys are not taken into account and averages for the entire BEV parc are assumed. These averages would need to be adjusted to represent any large shifts in national BEV vehicle usage patterns. A gradual improvement in battery technology has been assumed and modelled which in turn leads to a shift in the viability of BEVs. This has been accounted for in the model since the outputs from the Powertrain Technology module are used to influence the Vehicle Ownership module. In turn, the Powertrain Technology module is also influenced by the Vehicle Ownership module because the uptake of Battery Electric Vehicles (BEVs) has an effect on the battery production industry. Figure 9 shows a plot of the resultant BEV uptake curve where the number of BEVs starts to compete with the current ICE numbers by 2035 based upon an aggressive uptake rate beginning from 2015 onwards.

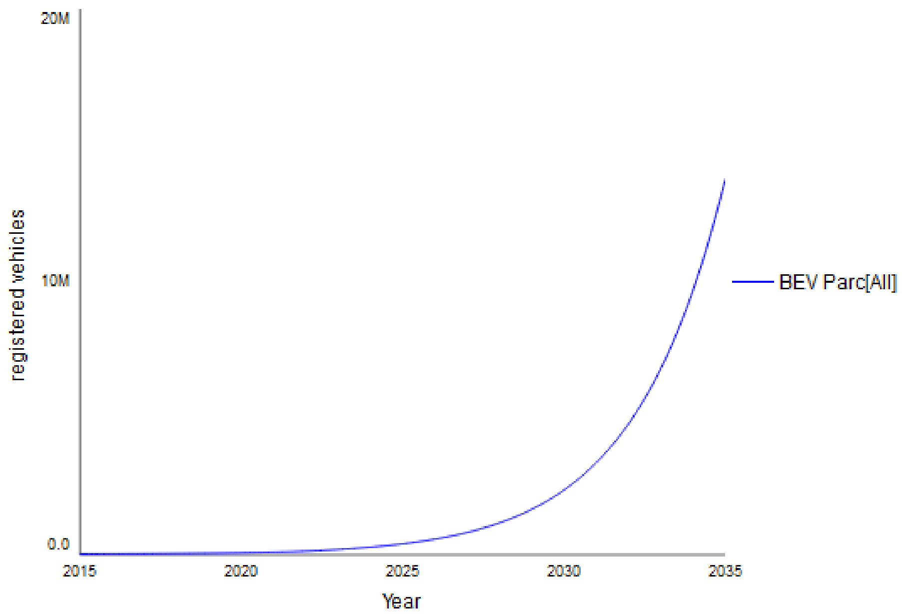


Figure 9:BEV Uptake Curve

Assumptions for this aspect of the model include:

- ICE development has plateaued or reached diminishing returns in terms of efficiency, so the effects of improvements (downsizing, turbocharging, and a return from Vee to in-line engines) are not modelled.

- Hydrogen vehicles (both fuel cell and direct combustion) have not been considered, but their challenges and influence could be considered to be similar to BEV.
- Hybrid vehicles have only been included in a limited sense of reducing idling emissions, but could be considered on the spectrum between ICE and BEV with appropriate adjustments made to the calculations.
- All values are typical averages for the whole electric vehicle fleet usage all year round combined.
- The Nissan Leaf has been used a starting point for typical values for range and battery specifications.
- Battery performance is assumed to improve along smooth curves, although in practice this type of technology often undergoes sudden step changes as new chemistries are developed and released. However, for the long term, smooth curves should be able to represent the net effect.

2.5.3 Infrastructure

The Infrastructure module has been broken down into Electricity Supply and Charge Points.

Figure 10: Infrastructure module structure

The Electricity Supply sub-module provides input for calculation of the CO_2 intensity of electricity used to power BEVs. The CO_2 intensity figures are based on the values for each type of generation (gas, nuclear etc.) and the proportion of each being used for the UK grid. This is required to help to not over represent the benefits of EVs use, since they are often reported as being zero emission when in fact they are not if the generation of electricity is taken into account. Average values have again been used. Since individual vehicle movements are not being modelled, location based effects are also not considered. Therefore, no direct account is made for the fact that a BEV which has been charged close to a wind turbine in rural Scotland may have obtained much of its power whilst incurring zero emissions coupled with much reduced transmission loss compared to the same vehicle which has been charged in the London area from a non-renewable source located at significant distance and thus having undergone powerline transmission and conversion losses.

The Charge Points sub-module aims to model the number of EV charge points in the UK, which will have an effect on the uptake of BEVs and Plugin Hybrid Vehicles (PHEVs). The overall viability of these vehicles is dependent upon a combination of the availability of charge points, the required charging time, the detriment to the batteries due to cycle depth, since these factors together will influence the vehicle's usable range and battery life. In the model, these factors have been treated together using averages, rather than attempting to model different battery life cycles based on different usage patterns created by different journey types. However, the full battery life cycle is important since, for example there will be a double effect that: Firstly, if it is used for long distances (such as a mid-range work commute) this will result in deeper charge-cycling and faster degradation (loss of charge capacity). Secondly, the user's need to change the battery pack (or the whole car) sooner since their minimum guaranteed journey length will be longer for that particular owner than for one who relies on the vehicle for shorter more local journeys.

2.5.4 Journey Characteristics

The Journey Characteristics module represents the journeys taken, which directly lead to energy consumption and emissions. There is considerable complexity in understanding all individuals in a population making separate journeys taking different routes with different start and end points in different vehicles for different purposes. All of these journeys currently add up to a total exceeding 300 billion miles per year. All of the subtleties of why, how, when and where these journeys are made will influence the cumulative total of the resultant energy and emissions.

The System Dynamics Modelling approach requires that these details are somehow logically grouped by some common characteristics. The DfT's National Travel Survey (NTS) (see further discussion in the Data section) introduces some journey classifications based on the reason for travel along with the percentages of journeys which fall into each of the groups. This forms a useful starting point for the groupings. Still, within each of the reasons to travel there will be people that make different journey lengths using different types of road to varying degrees. For this modelling exercise, it was therefore decided to further group the journeys into some standard journey types which are formed of fixed lengths, with composite use of different road types to which different energy/emissions characteristics can be attributed. The journeys are fixed so do not change with time as the model runs, but the total number of journeys made per year of each type can be varied to allow a net migration towards longer or shorter journeys being made. This allows for the modelling of scenarios such as those which lead to an increase in the total number of short shopping trips being made, and for people tending towards longer commutes while the total number of commutes stays the same. Some of the assumptions and limitations in the approach adopted for standardising the journeys are as follows:

- The order of the journey segments is not considered, only the total miles spent on each road type.
- Powertrain warm-up effects are not considered as these will be a complex function of journey length, road type (and order), seasonal variations, driving style and powertrain and vehicle specifics.
- Variations in driving style are not considered that may occur due to the journey reason, such as an aggressive time constrained commute vs a casual shopping trip.
- The actual composite journeys used are currently just illustrative and are not backed up by any data or research, but in the future can be substituted with the most representative ones, when known.

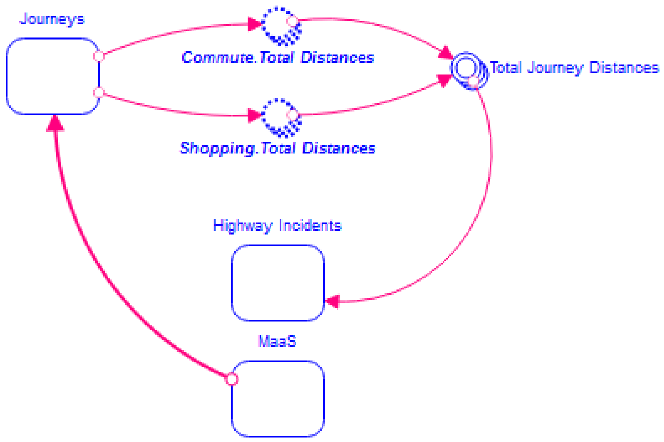


Figure 11: Journey Characteristics module structure

The Highway Incidents sub-module allows for the consideration of congestion due to incidents. The time spent not moving, or in slow moving traffic can be a significant contributor to the energy and emissions of vehicles. Factors which influence the frequency and severity of incidents and the number of vehicles suffering delay will influence the total impact on energy and emissions. Factors which influence the frequency and severity of incidents and the number of vehicles suffering a delay will influence the total impact on energy and emissions. The early adoption of ADAS features may have greater impact upon the occurrence rates and severity. Connectivity features may also help to reduce the numbers affected directly through incident prevention (due to connected ADAS) and indirectly by diversion and avoidance (through connected navigation and dynamic routing).

The MaaS sub-module aims to model the journeys expected to be taken once MaaS becomes available. It takes the population groups in the age ranges of 15-29 and 65-84 as potential user groups having the highest numbers of non-driving independent individuals and applies separate adoption curves to the two groups. Whilst it is entirely conceivable that people in the age range of 30-64 would also make use of MaaS, the most significant usage changes in terms of energy and emissions will come from current non-drivers gaining access to individual transport. MaaS lift sharing and coupling and platooning of MaaS vehicles have not been considered.

The Journeys sub-module is broken down into different types of journey. As previously mentioned, this has been initially based on the DfT's NTS. To date, the main two journey types have been considered: Commuting and Shopping. Parking has been considered as a separate part of a journey, then added to the different types. This allows, for example, the Connected Parking feature to affect all the relevant journey types.

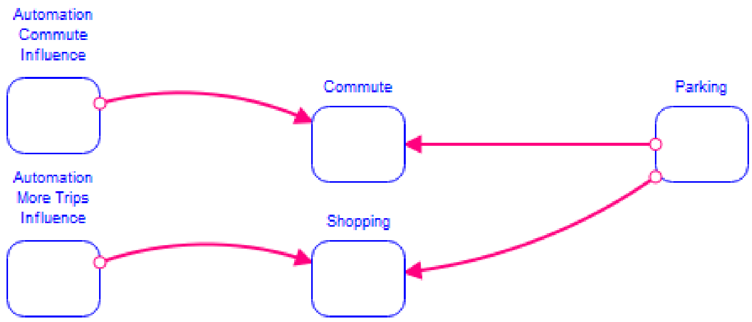


Figure 12: Journeys sub-module structure

Each journey type has been broken down into some assumed typical composite journeys made up of different segments. The segments are Highway (H), Rural (R), Urban (U) and Super Urban (S). Super Urban refers to dense, highly congested, urban areas. Examples of some composite journeys are shown in Figure 13. The number after the segment letters refers to the total journey length in miles. The number after the segment letters refers to the total journey length in miles.

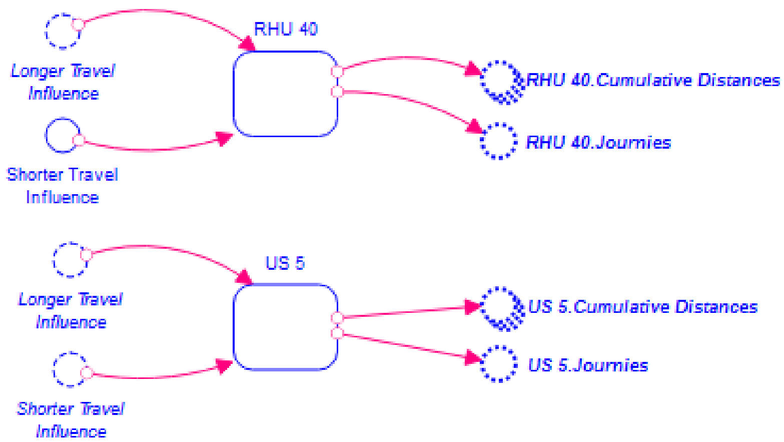


Figure 13: Composite journey examples

The Highway Incidents sub-module models attempts to address the effects of vehicles stuck in motorway closures. It models average delay time and the number of vehicles involved, also as an average. It provides a mechanism to account for the benefits of ADAS and connected features which don't directly influence emissions or fuel consumption on a normal journey, but which may still have an impact by reducing the stationary and slow-crawling time created by accidents and other incidents. ADAS features may prevent accidents and connected features may reduce the numbers of vehicles affected by actively diverting them to other routes. It is anticipated that the reaction and clean-up times of the responding emergency and highway services would be improved over time due to better coordination of waiting vehicles so that there are less obstructions and quicker dynamic lane closures.

The MaaS sub-module is used to model the potential increase of car usage coming from the section of the population who would otherwise be non-drivers. In its current form it does not attempt to model the change in usage patterns which may occur such as return to base empty. It is just considering that certain people who previously did not drive will perform journeys that they either otherwise would not have made, or would have made using other modalities such as transit or walking/cycling. It is assumed that Autopilot is a prerequisite technology which MaaS will follow and that existing drivers (or would-be drivers) will continue to use Autopilot when in fact a proportion of them they may opt to use MaaS instead. In this case, both would be automated journeys for which it is assumed that the energy/emissions difference will be less than the difference between manual driving and Autopilot. In reality there may be differences in vehicle performance choice and warm-up effects to consider between MaaS and Autopilot.

Assumptions:

- Parking distance assumes only a percentage of commuting (40% say) drivers have to use public parking at work that may require a significant search distance to find a free space. Only the destination half (non-home) of the journey is considered for parking.
- For Highway Incidents, Concrete Safety Barrier Coverage assumes a uniform likelihood of a particular barrier section being hit. In reality there will be hotspots which may get replaced sooner.
- No changes in speed limits as result of improved safety.
- No reduction in passive safety (weight reduction) resulting from active safety improvements.

2.5.5 Vehicle Ownership

The vehicle ownership model (shown in Figure 14) has been split broadly into vehicles with ICE and BEVs. The particular proportion of each ICE engine/fuel types (Petrol/Diesel/Hybrid) is not modelled directly, but where a distinction is required, such as for emissions calculations, a fixed ratio is applied at the point of use. Hydrogen fuel cell vehicles have not been considered, but it is thought their adoption and the issues with their use will be similar to BEVs (storage density, refill points infrastructure, vehicle range) and therefore this will not skew the overall results of the model.

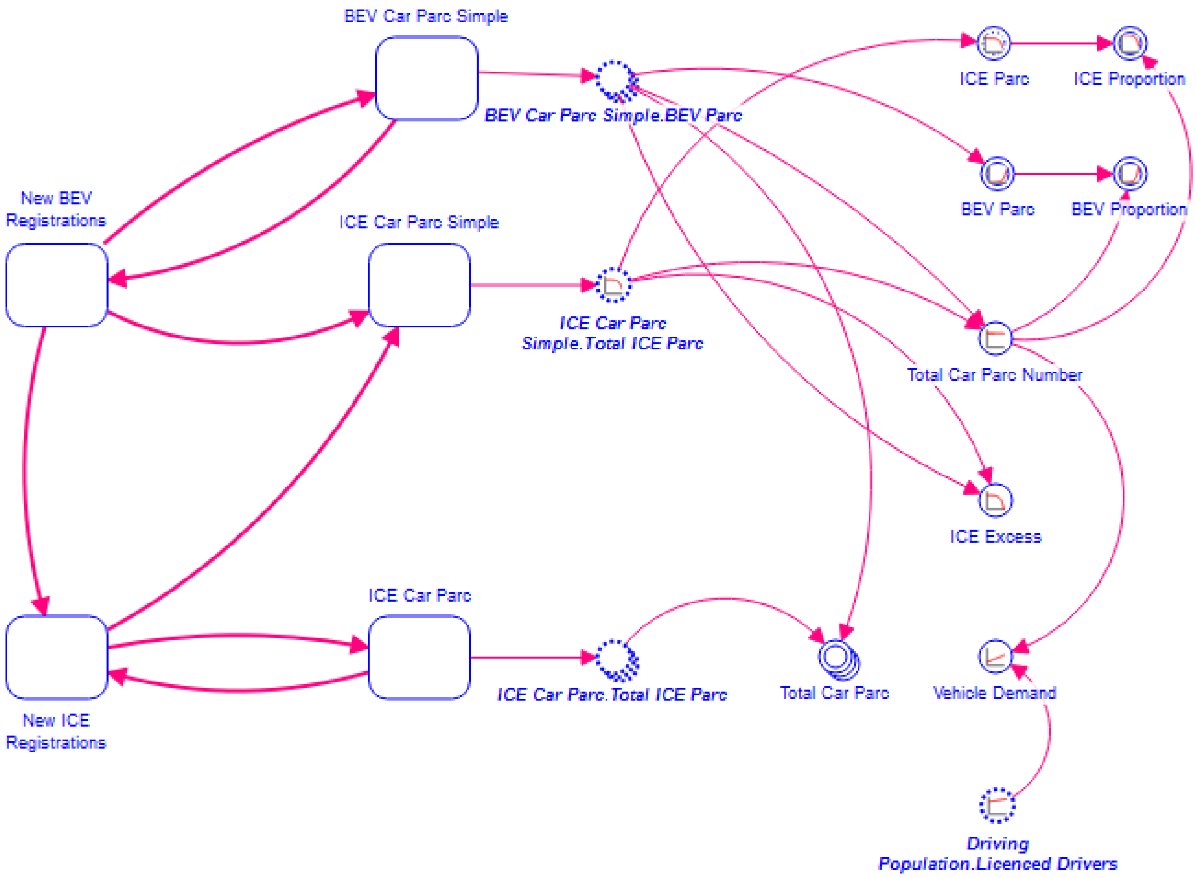


Figure 14: Vehicle Ownership module structure

As with the human population, the vehicle population, or parc, is made up of many different individuals, each with their own characteristics such as age, powertrain and fuel type. As with other sections of the model, the System Dynamics approach requires that groups are formed which contain members with similar characteristics that may in some way influence the model's output of energy and emissions. Data was found for an age grouped division of the UK vehicle parc. The modelling challenge was that the existing parc is constantly aging and can only be replaced by new vehicles. In order to keep vehicles within age 'bins' whilst allowing them to constantly be getting older as the model runs, a network of conveyors has been used. Each age bin is initialised with an even spread of number of vehicles registered in that age range. As the model runs, vehicles will progress from one age bin to the next. Leakage flows from each conveyor have been used to represent the premature retirement or scrappage of vehicles within each age bin. The vehicle parc model is shown below in Figure 15.

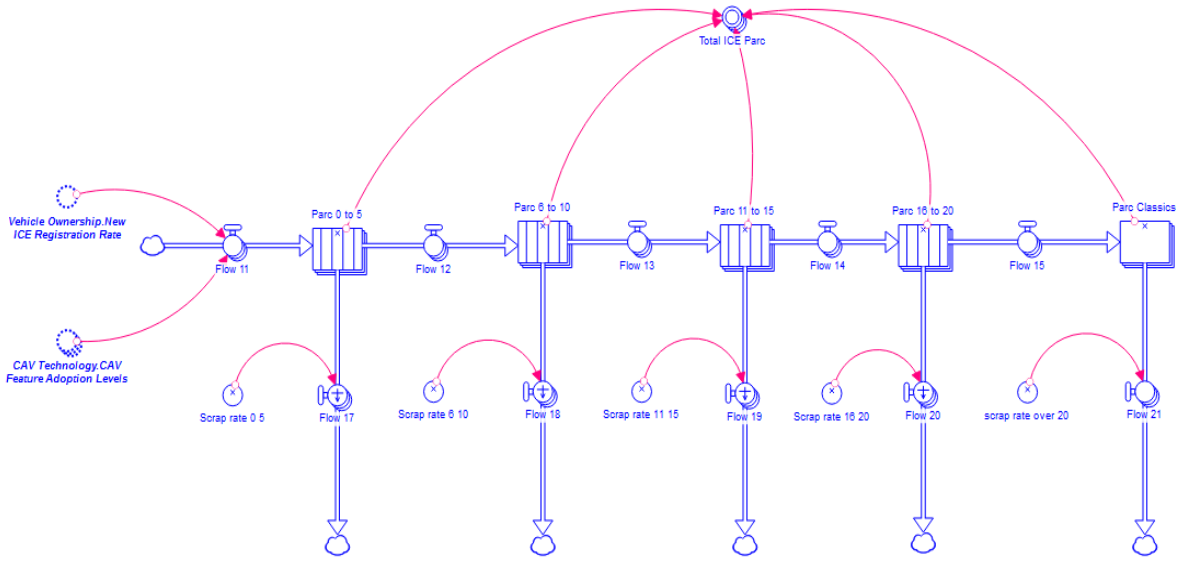


Figure 15: Vehicle Parc (population) Model

Since we are concerned with the adoption of ADAS and connected and automated features, the conveyors have been used in an arrayed form to allow additional attributes to be added such as feature fitment from their respective unit adoption rate models. This approach allows the number of vehicles with a particular feature fitted to be known at any time, which in turn allows the feature infiltration to be modelled for the whole parc. It does not allow the number of vehicles that have particular combinations of features fitted to be known. This is not thought to be a problem since the effects of features are considered separately without any multi-feature synergies or interactions being used. Also, scrappage rates have been applied equally to all vehicles within an age bin without any consideration that certain feature fitments may make a particular vehicle less prone to being one of the scrapped vehicles i.e. there is no survival of the ADAS fittest. There is also no feedback from the incidents sub-module to adjust overall scrappage rates based upon the level of success of ADAS/CAV features since in its present form scrappage rates remain constant throughout the model run time.

2.5.6 Population

The Population module (Figure 16) has been broken down into General Population and Driving Population. This has been done to enable full automation scenarios to be modelled. As discussed in relation to the CAV Technology module, there may be members of the general population who are not able to drive, but who would use or own a fully AV if it were available.

Figure 16: Population module structure

The Population module is not influenced by any other part of the model. It feeds into the Vehicle Ownership module. As with the vehicle parc, a network of conveyors has been used to represent the numbers of people within the age groupings, so that that age distribution will be aged as the model runs. It has also been divided in to males and females so that the differing birth and death rates can be applied, and so that if there are any behavioural differences related to gender, then these could be applied at a future date. The age groupings have been used to allow different vehicle usage behaviours to be applied against different age groups and to know the numbers in those groups at any time as the model runs. It should be noted that there is no adjustment to the birth rates based upon the growth or decline of the population within child bearing age, but it is felt that this still holds valid over the timeframe the model is run. As any changes to the current birth rates would take time to propagate to cause significant to the size of the population in the vehicle user age group, i.e. even if the birth rate saw a sudden jump now, it may be twenty years or so before there are more drivers in the population as a result. This would be particularly true before widespread MaaS introduction except perhaps for some changes to the number of certain journey types made by parents. Also, changes to current death rates are not modelled, and these could occur for example, due to the decline of serious vehicle incidents in-line with ADAS and CAV feature introduction, these have not been accounted for as this was considered a high-order effect that is difficult to quantify and with only a negligible effect upon energy and emissions.

Other assumptions include:

- Immigration/emigration are not considered.
- The high-order effect of improved transport efficiency bringing more workers to the country is not considered.

2.5.7 Energy and Emissions

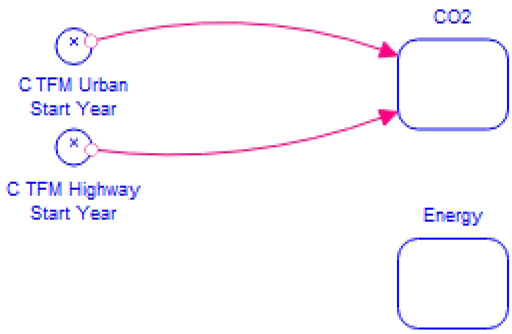


Figure 17: Energy and Emissions module structure

The Energy and Emissions module (Figure 17) aims to calculate the energy consumption and emissions resulting from the model. CO_2 is calculated based on distance and time within the sub-module (Figure 18). The different journey segments from the Journey Characteristics module are brought in separately as each is associated with a different average efficiency.

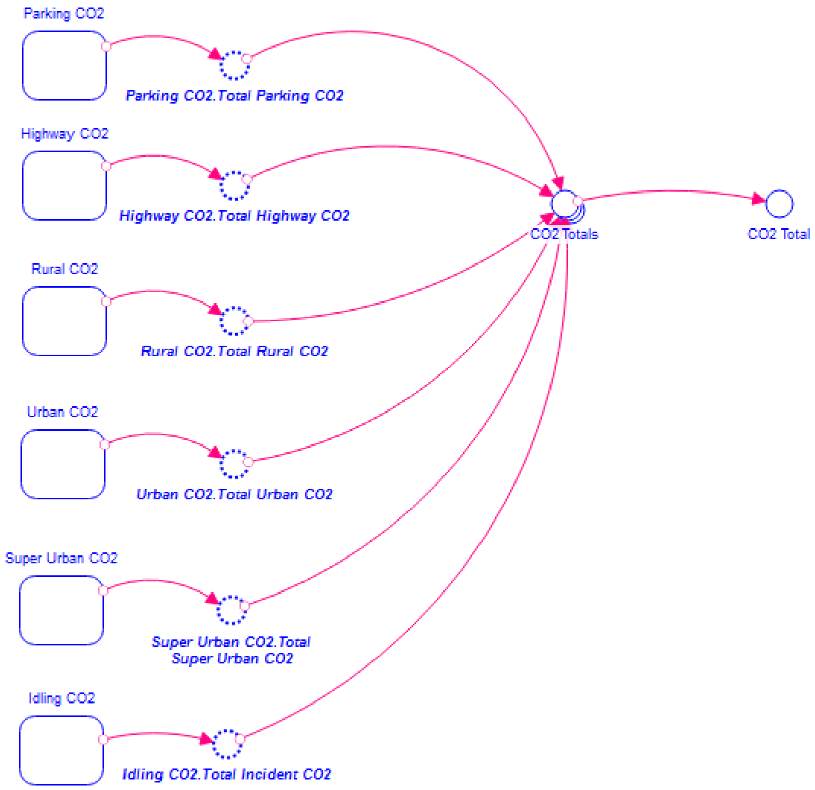


Figure 18: Emissions sub-module structure

CO_2 emissions are calculated based on the total distance travelled for each journey segment road type and average CO_2 per mile is applied separately against each road type. For idling, there is no distance covered, so average values are used for when a vehicle is stationary for each of the main powertrain types. In the model, idling refers to the abnormal time spent not moving due to a road incident. Normal idling time should be absorbed in the average CO_2 per mile value for each road segment type. So, particularly for the Super Urban road type the figure used for CO_2 per distance should absorb the amount typically produced under the stop/idle/start conditions of this road type.

The CO_2 per km is different for ICE and BEVs, so the calculation is split as a proportion of ownership of the different vehicle types. In theory, certain vehicle propulsions/powertrains may be used more for certain types of roads, for example BEVs may be used less on highways due to 'range anxiety'. The model does not currently take account of this, but it offers an opportunity for future refinement if the relevant data can be obtained to support it. An example of the calculation, for the Highway segment, can be seen in Figure 19 below.

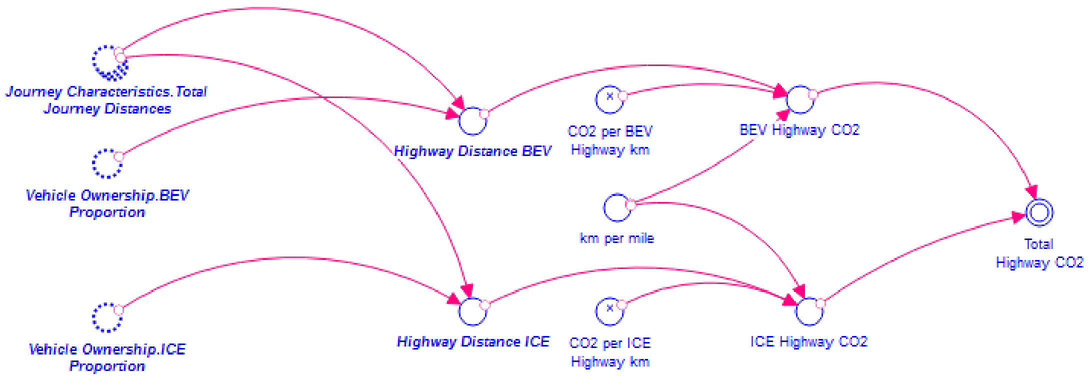


Figure 19: CO_2 by distance calculation example

The counterpart CO_2 due to idling time calculation is shown in Figure 20 below.

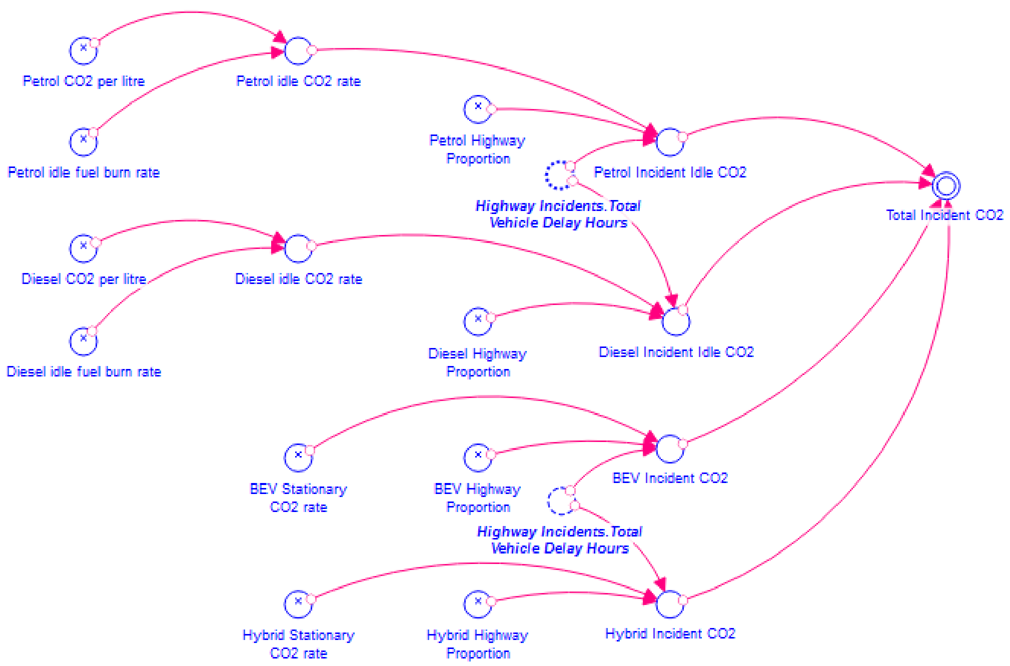


Figure 20: CO_2 by time calculation

Figure 21 shows a sample energy calculation for one of the road type categories (Highway). An average liquid fuel consumption per mile is assumed for all vehicles (regardless of size or petrol/diesel/LPG/hybrid fuel type) and used to calculate the total fuel volume per year. Likewise, for BEVs an average power consumption per mile is assumed for the particular road type and used to calculate the total energy per year (ignoring charging behaviours and inefficiencies which, from a Nissan Leaf testimonial, may average to around an additional 20%). Liquid fuel is then converted to an equivalent total power for comparison with electrical power.

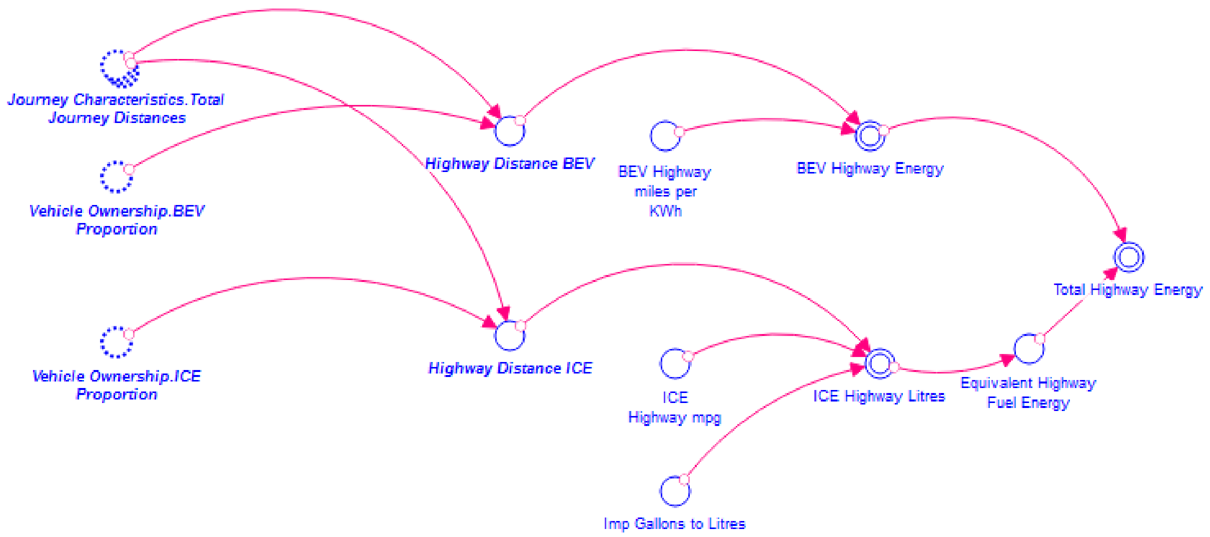


Figure 21: Energy by distance calculation example

3 Data

3.1 Data Sources

The scope of the model for this project is the passenger car transport system in the UK. Data sources have therefore been sought to provide input for elements of the model based on this scope. A number of UK-wide data sources exist, and then main ones used in this project are discussed below. Other sources are referenced in the Data Dictionary spreadsheet which is provided with the model.

Office for National Statistics: The Office for National Statistics (ONS) publishes official UK statistics related to the economy, population and society at national, regional and local levels. These statistics, at the national level, have been used primarily to inform the Population module within the model.

DfT National Travel Survey: The NTS is a household survey designed to monitor long-term trends in personal travel and is the primary source of data for personal travel patterns by residents of England within Great Britain. The survey collects information on how, why, when and where people travel as well as factors affecting travel (e.g. car availability and driving licence holding). NTS data have therefore been used to inform the Journey Characteristics module within the model. Data from other DfT studies and reports have also been used where appropriate.

DVLA Freedom of Information request responses: Information related to the driving population, including rates of licences being revoked or handed in, has been made public as part of Freedom of Information (FOI) requests to the Driver Vehicle Licensing Agency (DVLA). These data have been used in the Driving Population sub-module of the Population module within the model.

3.2 Data Limitations and Opportunities

One of the main limitations encountered throughout the modelling exercise was the availability of data in the formats needed for a sufficiently granular System Dynamics model. As discussed in the Methodology section, System Dynamics (unlike Agent Based Modelling) requires a certain level of aggregation of people or journeys. Deciding which groups to put these people or journeys into needs to take into consideration the types of data that are available. However, this proved very challenging in this modelling exercise using the data sources above and trying to model the system in question in sufficient detail. For example, in the Journey Characteristics module the journey types and lengths (or something similar) are necessary to enable effects of connected and automated features to be seen, but there were no data sources found which provide travel information in this sort of form.

As part of the further work for this project, it could be possible to work with those in the modelling and data areas of DfT to access more of the raw data related to the NTS or data input to and output from the National Transport Model (NTM). There could also be versions of the model developed to look at specific geographical areas for which rich data sources may be available.

This modelling exercise can also be seen as an opportunity to understand the transport system as it relates to CAVs better, and therefore help guide the collection of future data to be able to support more work in this area.

4 Scenarios

4.1 Introduction

The System Dynamics relationship model developed in this project can be used to explore potential future scenarios. As well as making predictions based on data provided and the model's calculations, the structure of the model can also support policy makers' understanding of the system and therefore idea generation regarding potential policy options. In the case of this model, the timeframe considered is from the present day up to the year 2035.

The scenarios below have been chosen to show some of the kinds of policies that the model can help to inform and take into consideration. It is important to note that conclusions should not be drawn from the numerical values given in this section due to the lack of complete, accurate data currently used in the model. The graphical output provided is presented for illustration purposes only.

4.2 Scenario 0: Nothing really changes

In this scenario there are no significant changes from the current trends. There is a slow uptake of ADAS features (being mainly fitted to premium vehicles or vehicles with a particular safety marketing emphasis, and often at additional cost to the vehicle purchaser). Connected and connected ADAS features do not become a reality. BEV numbers continue to increase slowly as niche vehicles. Also, connected traffic flow management does not come into play so congestion and incident rates remain high. High automation features do not become available to any significant extent and MaaS has very limited if any at all uptake.

This scenario is presented to provide a baseline by which the others can be compared, as well as being a pessimistic but plausible outcome. As with the other scenarios, the potential effects due to population growth and economic factors are not included. Figure 22 and Figure 23 show that there are no noticeable changes to CO_2 emissions over time.

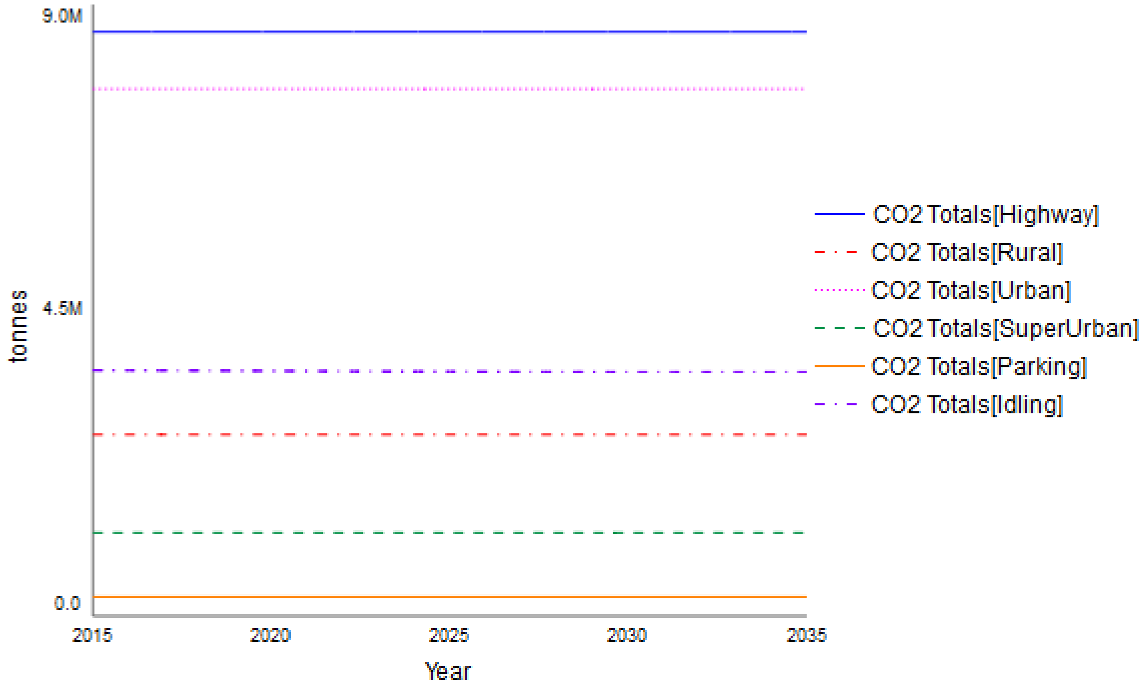


Figure 22 : CO_2 outputs over time against road category for Scenario 0

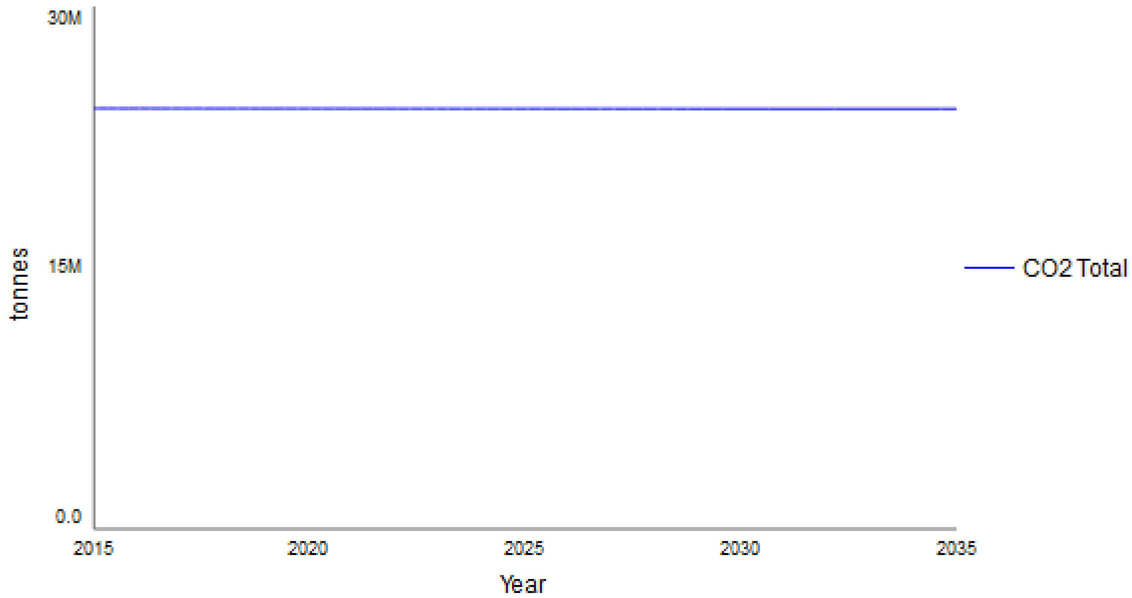


Figure 23 : Total CO_2 output change over time for Scenario 0

4.3 Scenario 1: Driver always in control

In this scenario, at least as far as 2035, the UK Government does not permit drivers to ever fully relinquish responsibility for the driving task, or otherwise, the technical and regulatory challenges that need to be overcome for higher automation level to be brought to the market are not met. In either case, this would mean that drivers could never be completely 'out-of-the-loop', so automation technology would only be deployed up to SAE level 2. If drivers must always be paying at least some attention to the road, it would not be legal for them to carry out a secondary task, such as working or reading. Therefore, any effect on the distance drivers choose to travel would be negligible, and automated MaaS would not be possible on public roads.

With automation only allowed up to SAE level 2, eventually almost all vehicles would have ADAS and Connected-ADAS (C-ADAS) features which would improve traffic flow and reduce accidents, but there would be no significant change in journey characteristics. This scenario is therefore likely to be one of the best cases in terms of energy consumption and emissions.

This scenario allows for a marginal increase (relative to the total vehicle parc) in BEVs to take place. Since BEVs are considered to be Ultra Low Emission Vehicles (ULEVs), any substantial increase would also have a substantial impact on the CO_2 emission totals. The BEV growth curve can be seen in Figure 24. It is useful to constrain the growth of BEVs within the parc for this scenario to allow the effects of ADAS and connected features to be seen.

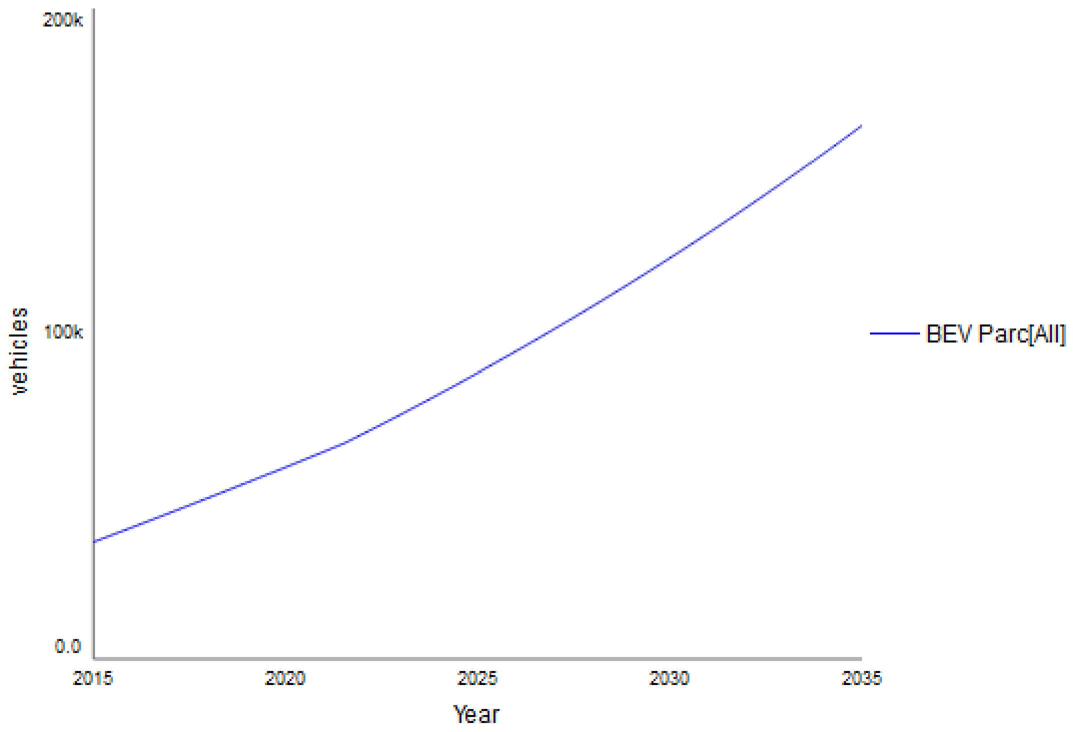


Figure 24 : BEV parc increase for Scenario 1

The adoption and parc penetration of the various ADAS and connected features along assumed arbitrary growth curves can be seen in Figure 25.

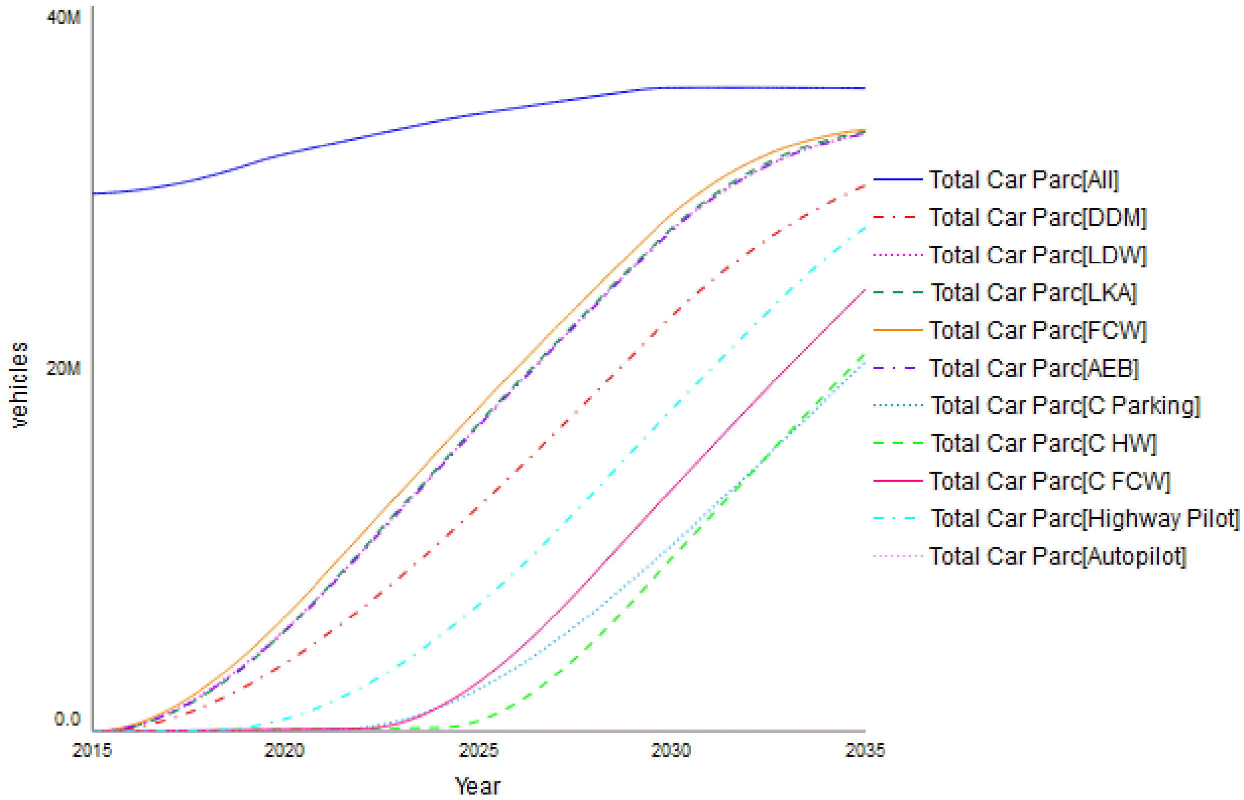


Figure 25 : Connected, ADAS and automation feature parc penetration for Scenario 1

Figure 26 shows an increase in highway mileage resulting in part from Highway Pilot encouraging a migration towards longer commutes, and also from a slight increase in the number of driving licence holders (due to current test pass rates and a continuation of current licence retirement and death rates).

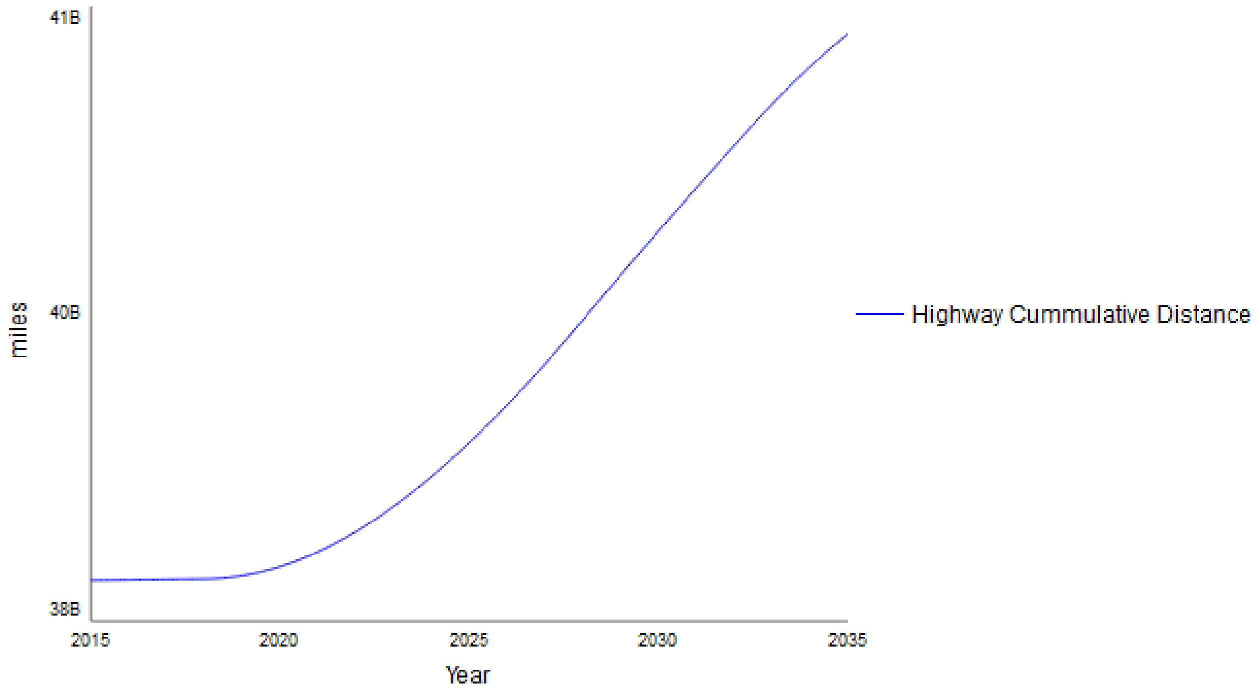


Figure 26: Increase of highway mileage in Scenario 1

The introduction of active safety ADAS features combined with optimisation of highway clean-up procedures results in a significant reduction (but not full eradication) of highway incidents and total road delay hours. The reduction of incidents and delay time is shown in Figure 27.

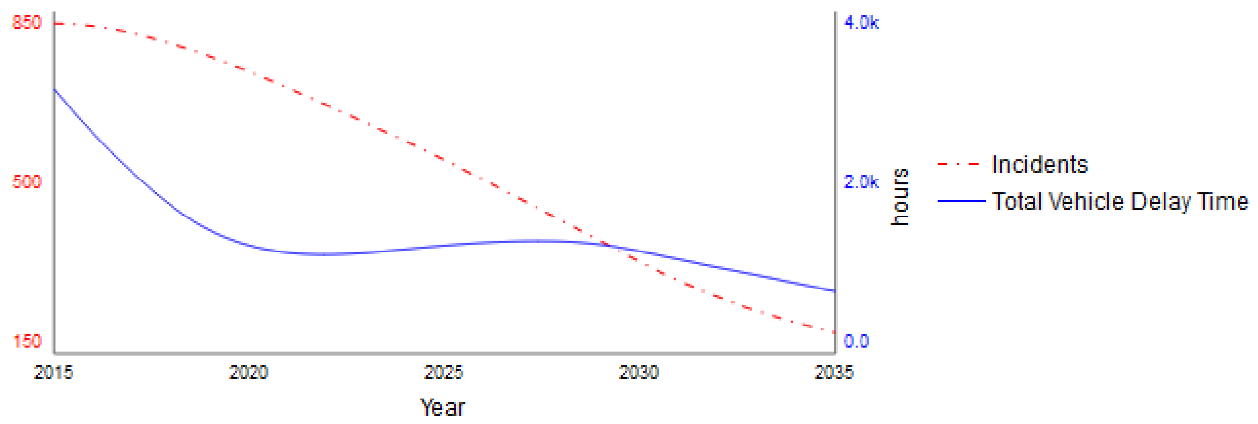


Figure 27 : Reduction of highway incidents and delay hours for Scenario 1

Figure 28 shows that the distances travelled remain largely the same apart from a slight migration from urban to highway commutes due to Highway Pilot adoption encouraging a slight increase in the numbers of longer distance commuters. There is also a reduction in parking search distance brought about by connected parking services becoming available.

Figure 28 : Total road mileage by road category for Scenario 1

The connected parking feature has brought about the reduction in parking distance and the curves for feature adoption and reduction in search distances are shown in Figure 29. There is a progressive reduction in search distance due to search algorithm improvement with time, the increased availability of car parks which can use the feature, and the gradual adoption of the feature by users. The average search distance is the total search distance for all parkers including both those using and not using the feature.

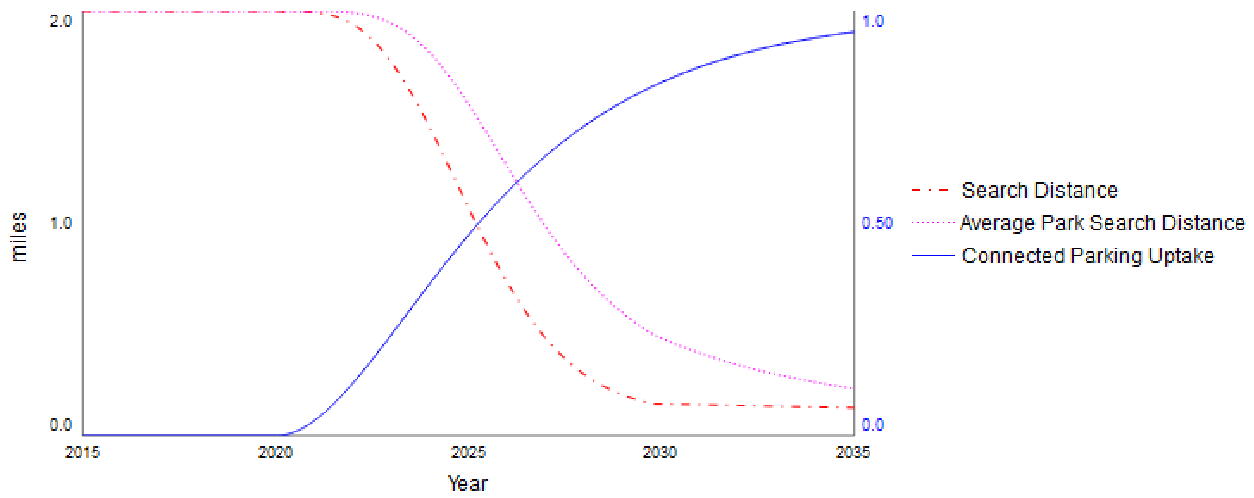


Figure 29 : Reduction parking search distance against connected parking uptake for Scenario 1

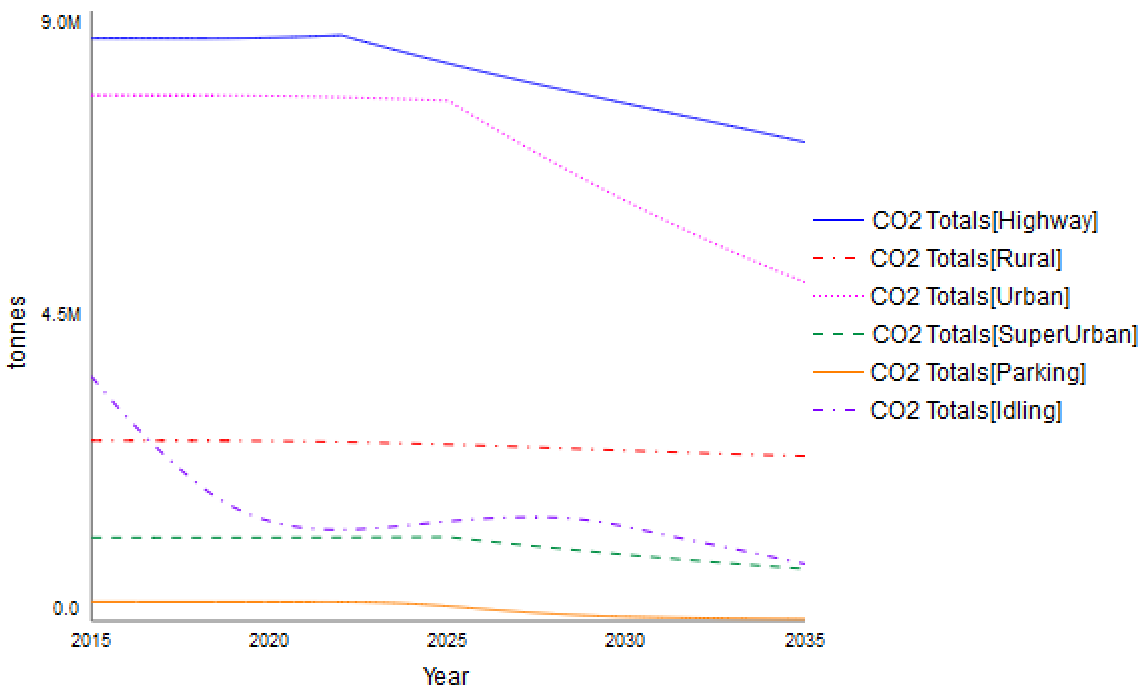


Figure 30 : CO_2 outputs over time against road category for Scenario 1

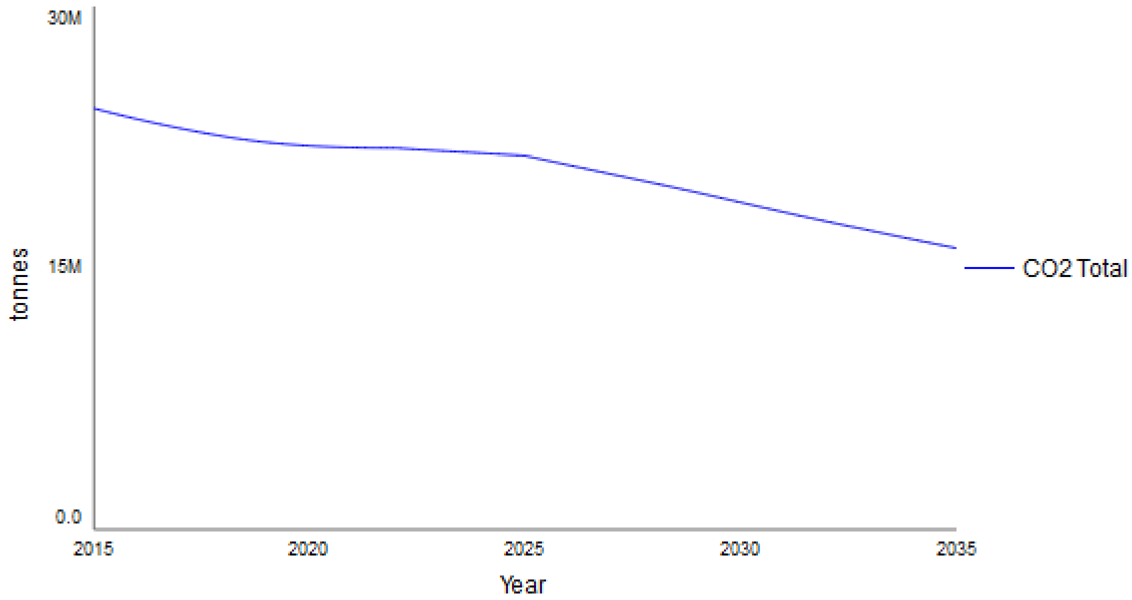


Figure 31 : Total CO_2 output change over time for Scenario 1

There are also assumed improvements to traffic flow in both urban and highway conditions due to improved traffic via connectivity, although no specific features have been created for this. Figure 30 and Figure 31 show the resulting reduction in CO_2 levels created by the combination of better traffic movements, fewer incidents and a slight increase in the numbers of BEVs on the roads. This happens despite the increase in road miles which occur due to more road users and longer journeys.

4.4 Scenario 2: No CAV regulation

In this scenario, the UK Government takes a very permissive approach to the development and deployment of CAV technologies. Assuming the technical, legal, regulatory and insurance challenges are all overcome over time to allow fully AVs to be used on the public highway, these technologies begin to be deployed within the next twenty years.

Initially, this scenario looks similar to Scenario 1, with uptake of ADAS and C-ADAS features making journeys more efficient. However, once SAE level 4 features such as Highway Pilot are available, drivers will be able to disengage from the driving task during dual carriageway driving, leading to longer commuting distances becoming acceptable. Then, SAE level 5 (full automation) will enable those without licences to use cars, and MaaS journeys will also increase.

This scenario contains the caveat that no specific advanced connected traffic flow management is employed, apart from passive forms such as incident avoiding navigation systems. It assumes that automation systems operate independently from each other and act to assist or replace the human driver without any direct collaboration between each other beyond that of connected hazard warnings. The result of this is that general traffic flow does not improve but the rate of incident occurrence continues to decline.

This scenario may be one of the worst in terms of energy consumption and emissions, although improved mobility and fewer road incidents are arguably still of wider benefit to society for reasons such as social inclusion and economic prosperity (ability and willingness to work and spend). While there are a number of benefits and efficiencies to be gained from automation and connectivity, the lowered cost of travel time, and ability for non-driving licence holders to use private vehicles may to lead to a larger distance travelled by car.

Key assumptions are:

- The current model structure dictates that there is no migration from owner-driver autopilot use to full MaaS in this time-frame, and that MaaS users are 'would-be' non-drivers. These assumptions do not hold strictly true, but it is felt that they are valid enough to show the general effects of automation uptake.
- The uptake in vehicle automation does not increase the number of daily commutes being made, but does lead to a net migration towards longer commutes. Changes to working-from-home trends are not considered; journeys get longer but the same basic number of people travelling to and from a place of work.
- The uptake in vehicle automation does not increase the length of shopping trips, but does increase the number of trips being made. This is mainly due to the increased access to transport of more users combined with the increased convenience. It ignores other trends such as the rise of internet shopping over travelling from the home to a retail unit. However, even with internet placed orders, deliveries still have to be made and intelligent mobility may play a part in this.
- Additional journeys generated have been biased towards short journeys (90/10) for MaaS. Without this, there would be an over representation of the CO_2 resulting from Highway journey segments and would otherwise likely overstate the overall CO_2 increase.
- The MaaS ownership model is not yet understood, so the vehicle parc has not been modified for this scenario. Open questions remain such as:
  - Could peak demand still be met if people give up their cars and they become privately fleet managed?
  - Would as many vehicles be needed?

Figure 32 shows the increase in highway distance travelled (as a national total) resulting from the uptake of automation features shown in Figure 33. The most pronounced change comes from the introduction of Autopilot since this allows the vehicle to drive without supervision for the first time which makes much longer commutes more viable from a time and fatigue perspective. Shorter days at the office could be envisaged for many as travel time between home/work/meetings/customers can be usefully employed 'on the road', with even the possibility of conferencing to the extent which cellular networking allows.

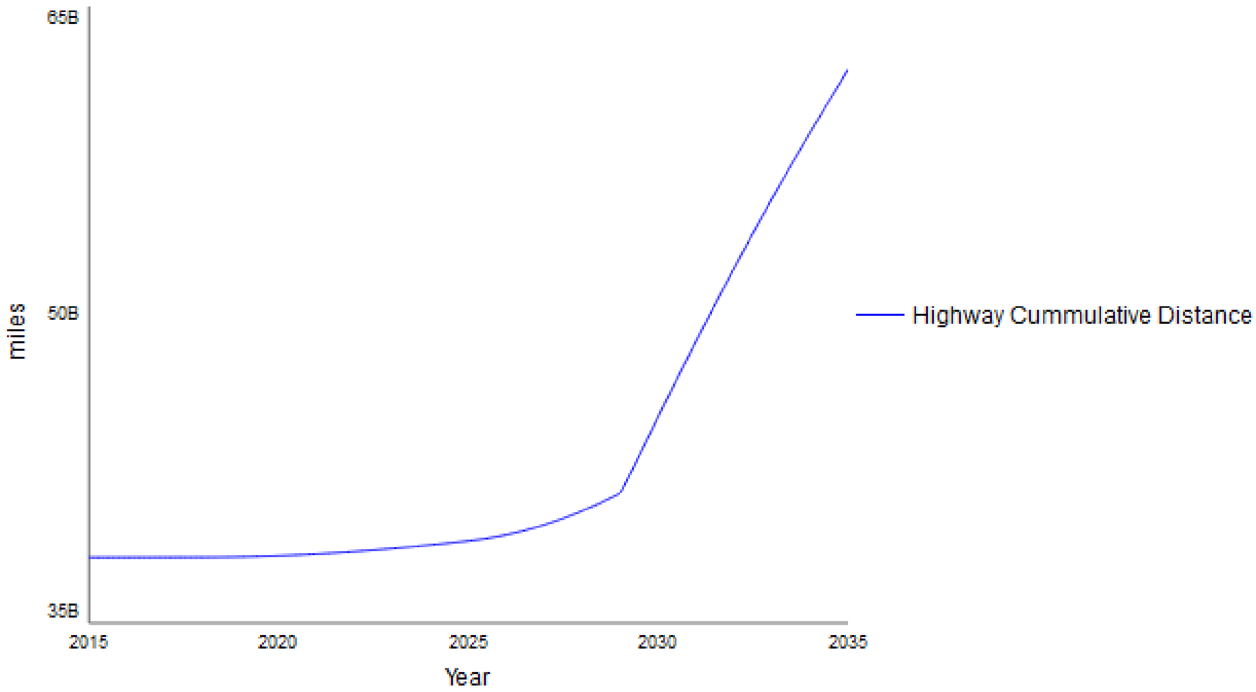


Figure 32 : Increase in highway mileage as longer commutes increase

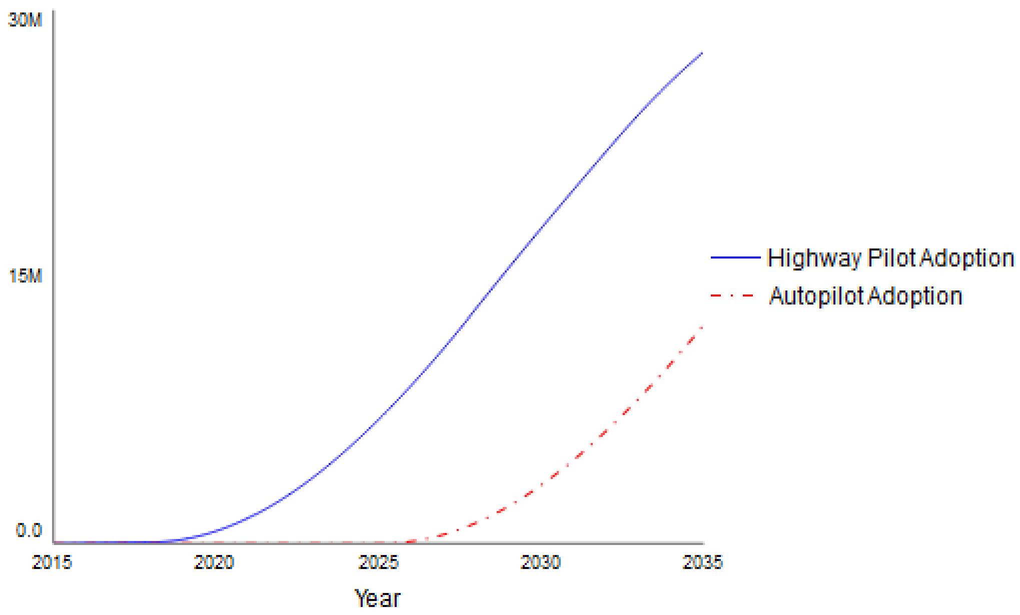


Figure 33 : Adoption of high automation features with time

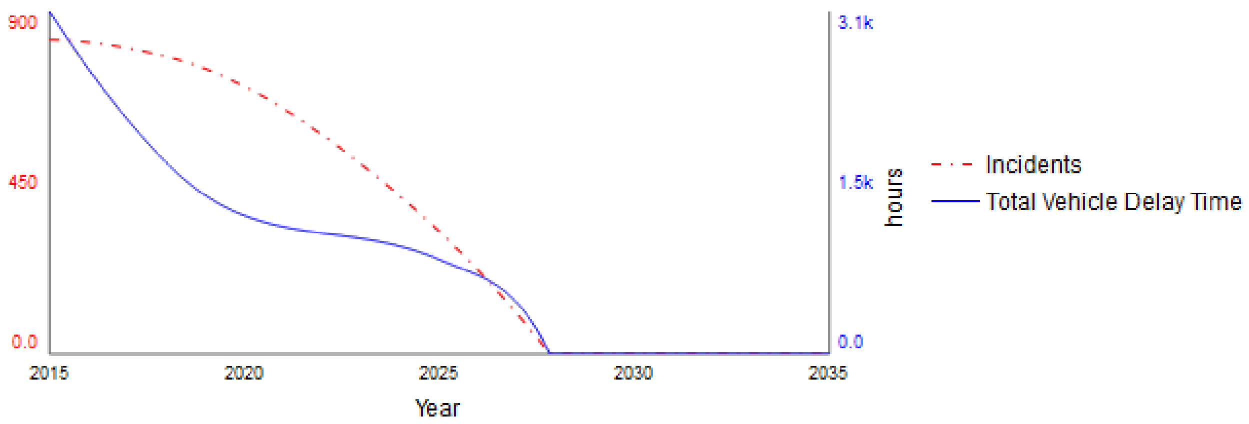


Figure 34 : Road incidents and associated delays approach nil once automation becomes prevalent

Figure 34 shows a steady decline in the number of highway incidents occurring, eventually being eliminated, by the prevalent use of high automation features. The initial decline results from ADAS and connected ADAS features becoming more commonplace. The delay time also reduces due to assumed improvements in the 'clean-up' efficiency. Connectivity will allow faster and more precise notification of incidents, and allow more free passage of emergency and recovery services to the incident location. This could occur from easier dynamic lane closures, assisted lane merging, and drivers being informed more clearly and in better time of the need to clear the way for service vehicles.

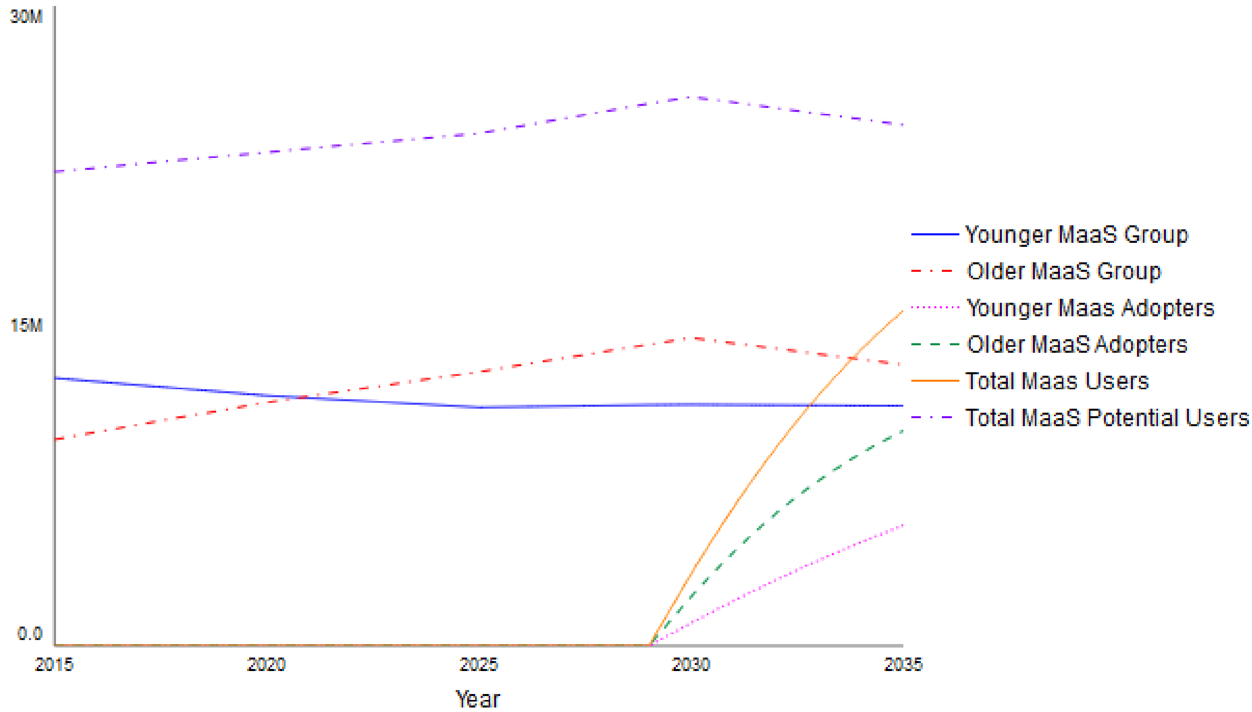


Figure 35 : Numbers of potential and actual MaaS users from the most benefited age ranges

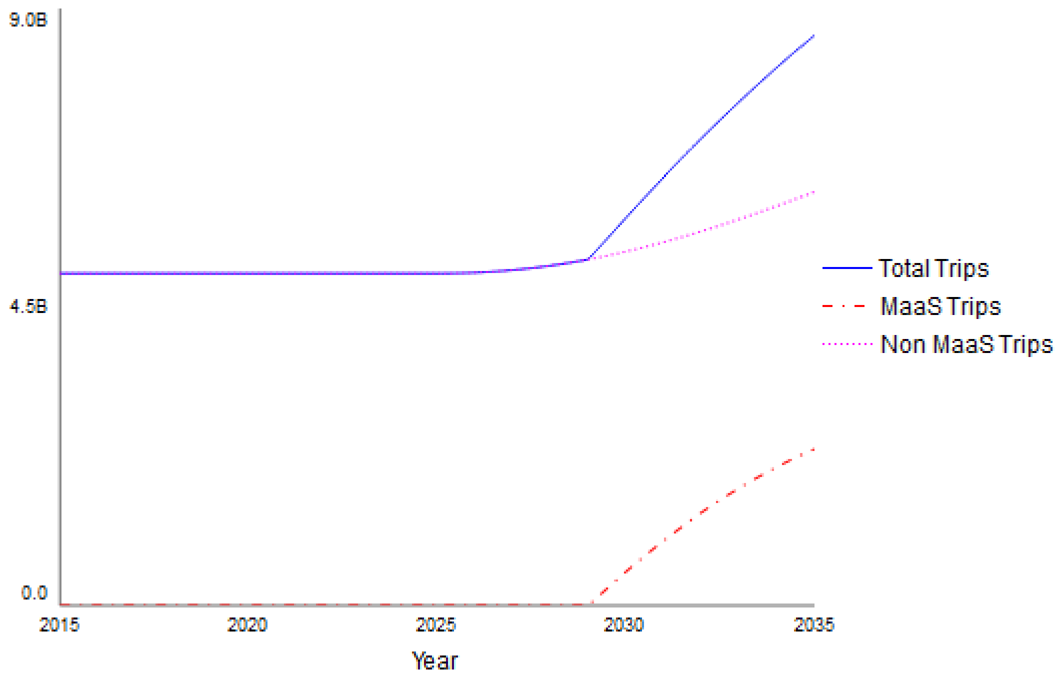


Figure 36 : Increase in the number of trips as MaaS personal mobility becomes accessible

Figure 35 shows the population sizes of the groups selected as being the most likely beneficiaries of MaaS, namely those of teenagers and young adults as well as older adults. Also shown are the modelled adoption curves for each of these groups as well as the overall total users from both groups. Although it is hard to speculate how each age group may receive the new MaaS services, it is conceivable that they may have different uptake rates as with all technology changes. Although it seems that the older group adopts quicker, it should be noted that the initial population size is larger and the younger group may be more likely to resort to other forms of transport depending upon their actual age and income. Figure 36 shows the overall increase in trips being made resulting from MaaS against the existing baseline of trips that would be made regardless. The baseline increases without MaaS due to the added convenience of other Non-MaaS automation such as Autopilot. Figure 37 shows the overall increase in distances for all road types which occurs due to the overall increase in travel and a migration towards longer commutes indicated also by the pronounced increase in highway distance.

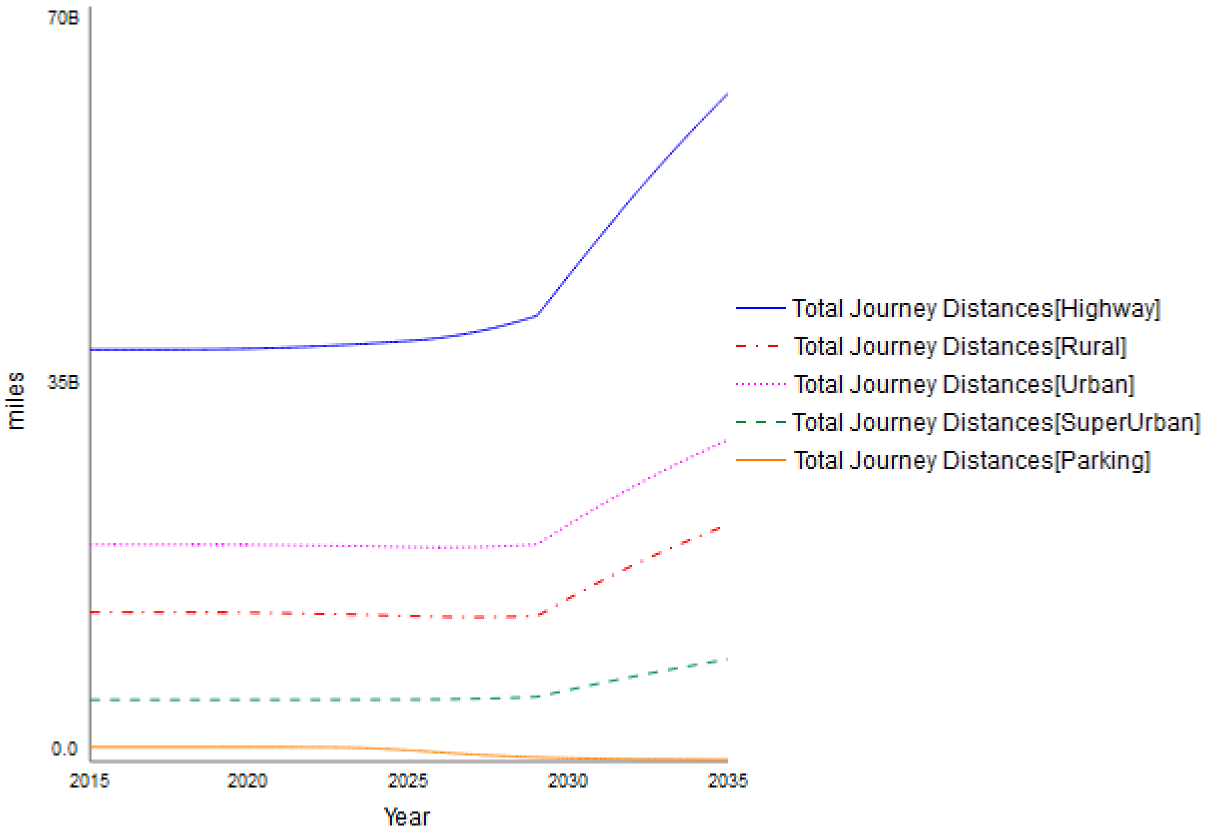


Figure 37 : Journey distances for each road category for Scenario 2

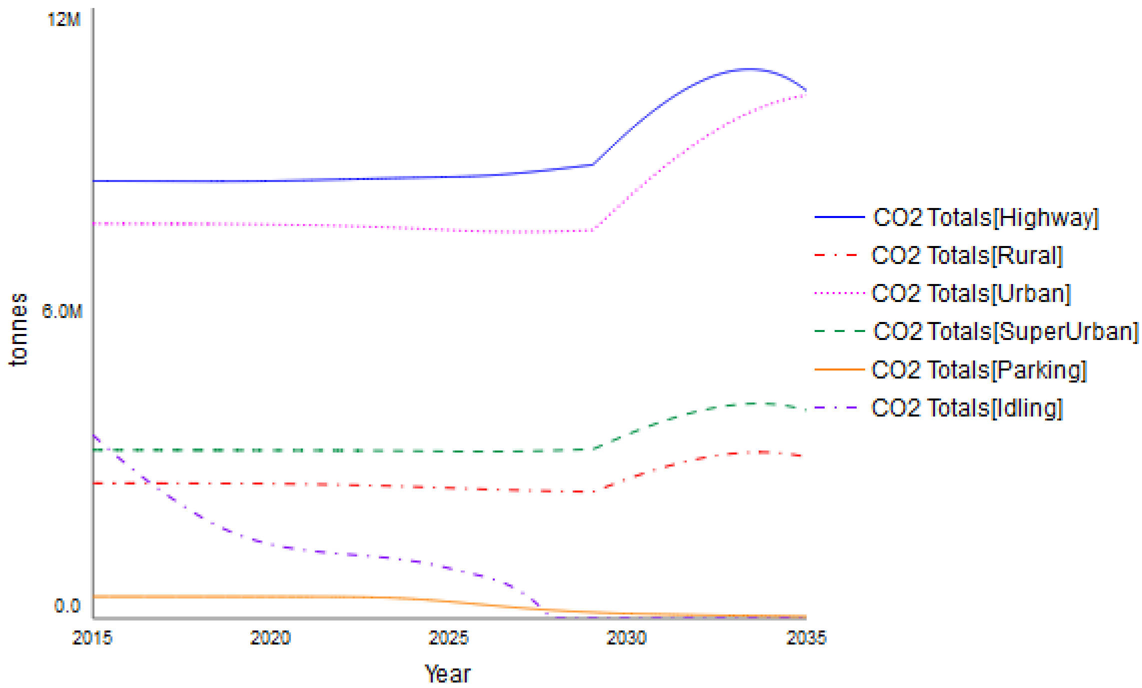


Figure 38 : CO_2 outputs over time against road category for Scenario 2

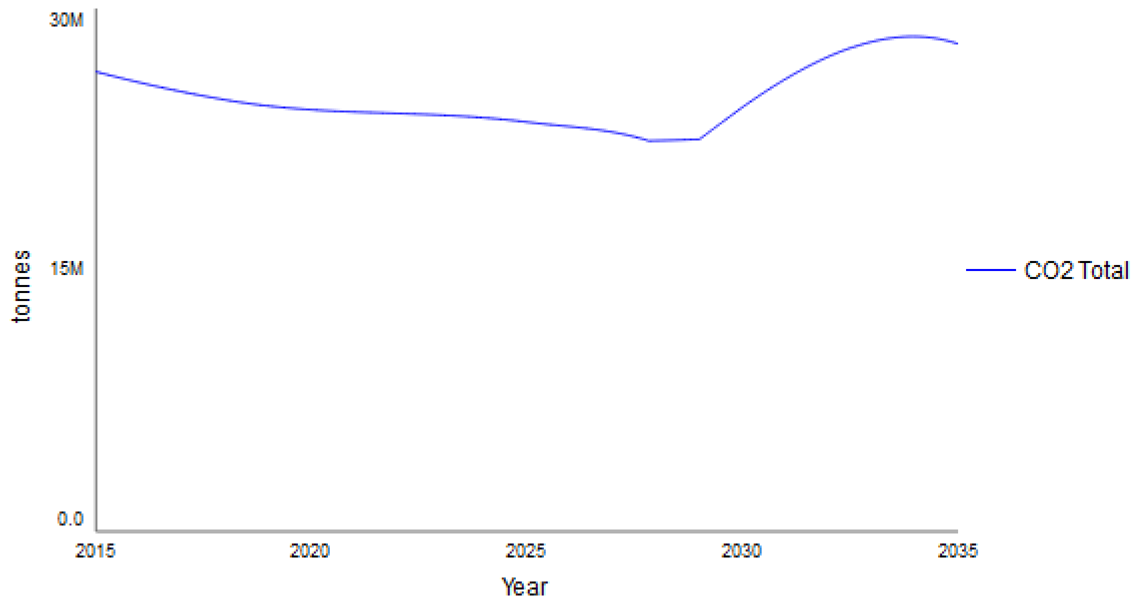


Figure 39 : Total CO_2 output change over time for Scenario 2

Figure 38 and Figure 39 show a steady decline in CO_2 followed by a prominent rise which brings the levels to exceed their starting point. Efficiencies gained due to reduced incidents, better parking, and a gradual move towards BEVs are offset by the longer and more frequent journeys led by automation. This result may bring some societal and economic benefit, but is contrary to the UK Government's current commitments to CO_2 targets.

4.5 Scenario 3: ULEV mobility

Looking at Scenario 2, it is possible to see that a complete lack of regulation in relation to the CAV market may not offer the best outcomes. While there are great social benefits to be gained from increased mobility for vulnerable groups and reduced road deaths due to increased safety, there is also the potential for an increase in car miles travelled, leading to more congestion and higher energy usage and emissions. In order to mitigate the potential negative effects of increased automation, a number of policies could be envisaged. One such policy idea is given as an example in this scenario. This idea is not intended to necessarily represent a viable policy and is not a recommendation of this report. It is used only as an illustrative example to demonstrate the types of scenarios which can be considered using the System Dynamics model.

In this scenario, the conditions are similar to those in Scenario 2, but with two significant differences. The first difference is that fully AVs (whether privately owned with an Autopilot feature or as part of a driverless MaaS fleet) can only be licenced if they are ULEVs. In the model, ULEVs are represented by BEVs. The second difference is that the emissions for each road category have been gradually adjusted to account for the introduction of connected active traffic management which should eventually relieve or totally remove the day to day congestion which occurs from high traffic volume and the limitations of current driver-to-driver arbitration.

The input to the model for this scenario is a change in the BEV uptake rate from the currently expected trajectory to one with a steeper uptake at the point that fully AVs become market-ready. The steeper uptake occurs due to linkage between the number of Autopilot and MaaS trips being made and the new BEV registration rate. Due to the current model structure, there is no early retirement of ICE vehicles to offset the increased BEV uptake, which might happen in reality because of the obsolescence created by automation. Figure 40 shows how the number of automated trips made increases once the high automation features become available. Shopping trips dominate over commutes in number but are considerably shorter in journey length.

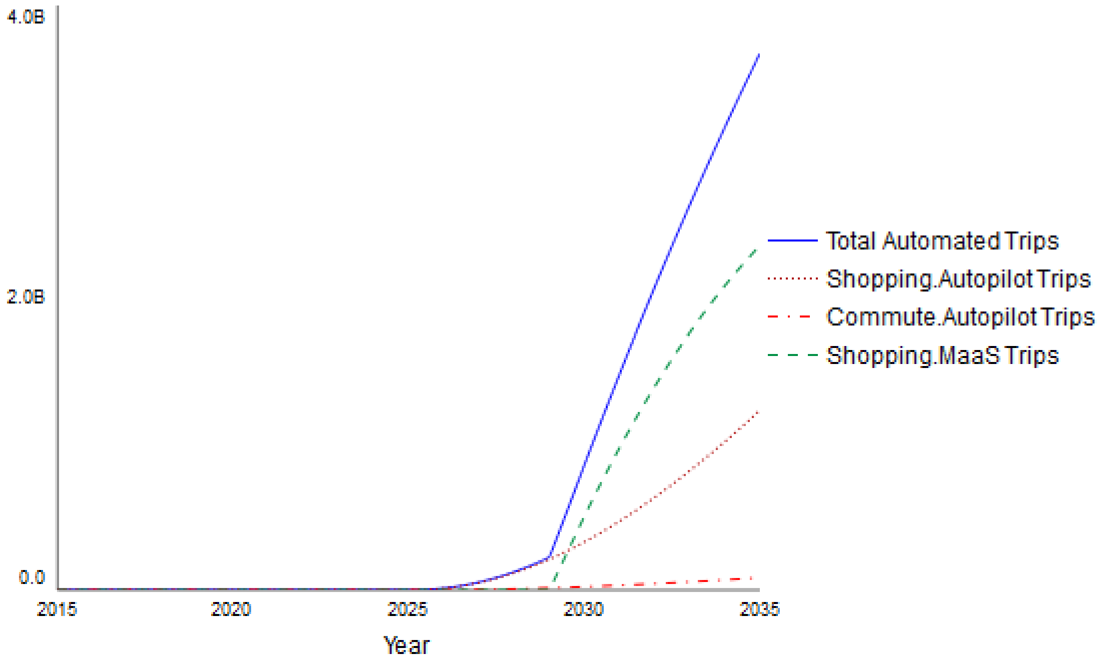


Figure 40 : Increase in automated trips per annum with time

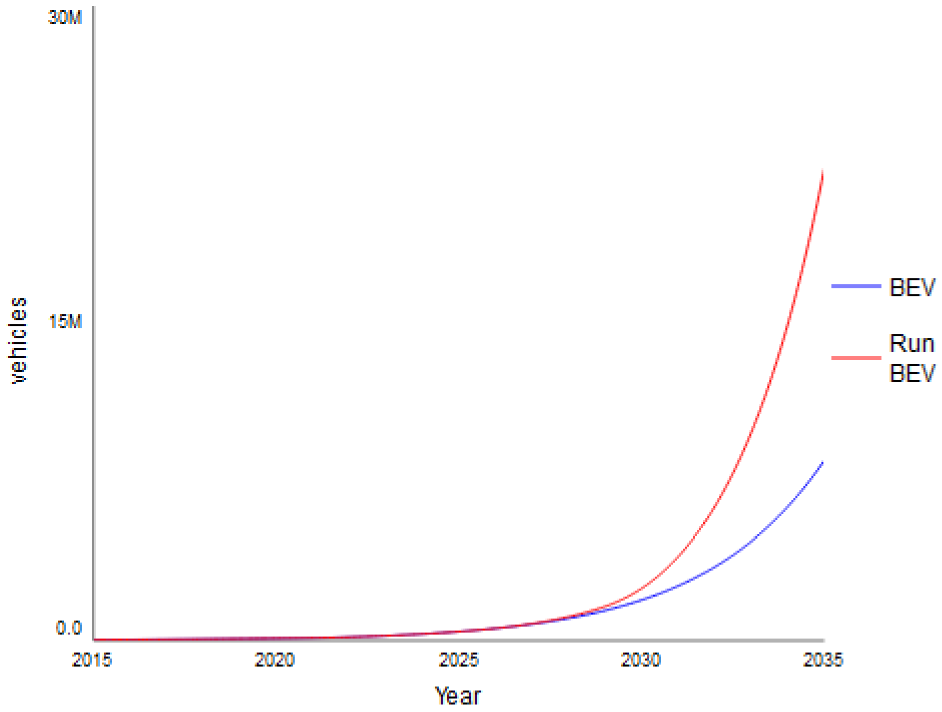


Figure 41 : Increase in BEV parc with ULEV policy (red) and without (blue)

Due to the influence of the ULEV policy upon BEV registrations, Figure 41 shows the marked increase in BEV uptake. Contrary to the previous scenario, the combined influence of connected traffic management and the policy-induced higher BEV uptake together result in a marked decrease in CO_2 for all road categories (Figure 42) with a fall to less than half of the overall starting level (Figure 43). This represents a success for improved personal mobility and the environmental commitments which need to be met.

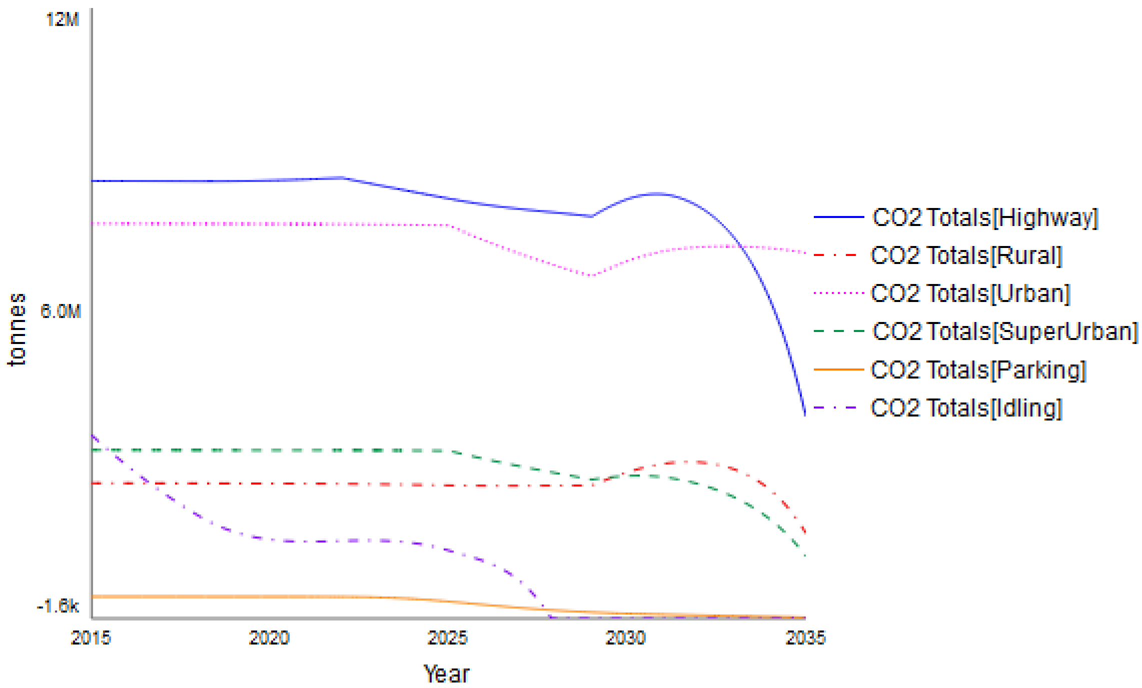


Figure 42 : CO_2 outputs over time against road category for Scenario 3

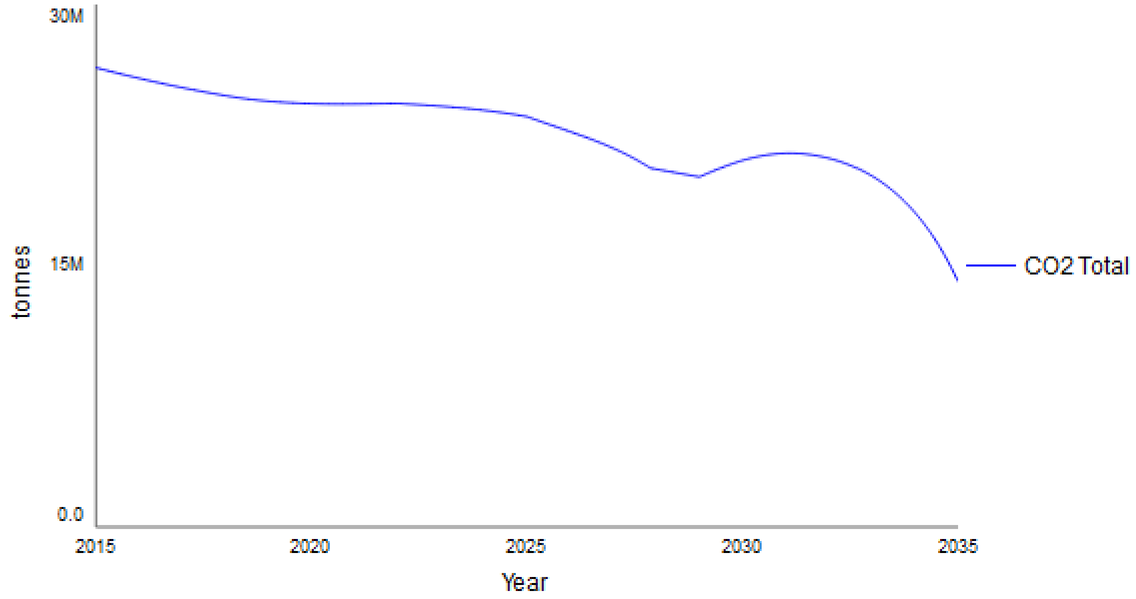


Figure 43 : Total CO_2 output change over time for Scenario 3

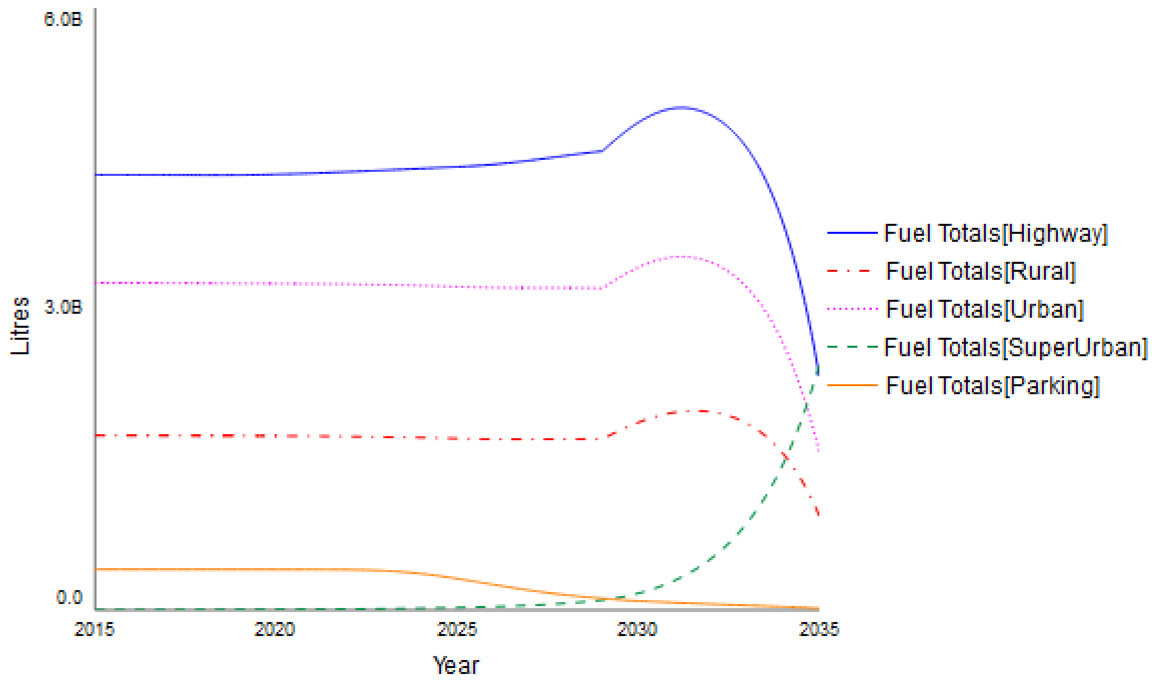


Figure 44 : Total fuel consumption change over time for Scenario 3

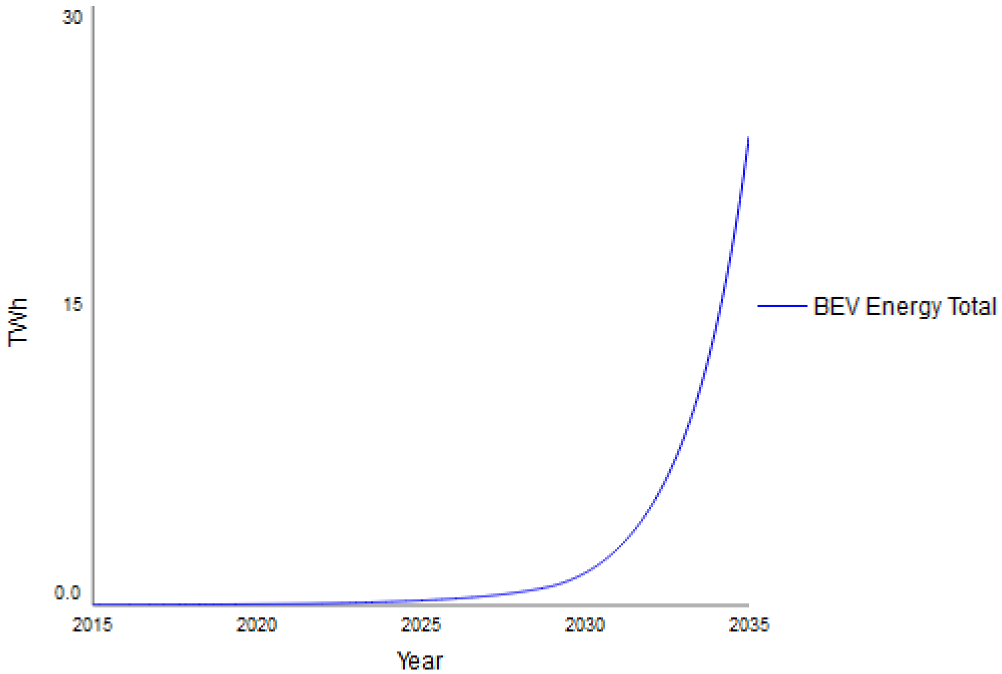


Figure 45 : Total electrical power consumption change over time for Scenario 3

Figure 44 and Figure 45 show the change to fuel consumption and electrical power used respectively for the third scenario. The reduction in liquid fuel burn mirrors that of the CO_2 reduction as expected. The extra power needed for BEV charging is significant and would no doubt require changes to the National Grid to be made to support this through domestic supplies. The actual figure for power supplied would likely be in the order of 20% higher to cover charging losses and a further 148% higher to cover the powerline and conversion losses in the electrical grid. So of the 13TWh (Terra-Watt-hours) of on-road usage predicted by the model for 2035 in Scenario 3, 23.1TWh would need to be generated in power stations or otherwise, and this difference should not be forgotten when considering the CO_2 differences between ICE and BEV vehicles.

4.6 Concluding Remarks

There are an almost overwhelming number of possible interactions and considerations which could lead to an almost infinite number of research avenues in the pursuit of understanding the response that the predicted large technological change in road transport could bring about. However, many of the feedback loops may turn out to be quite subtle and may not impact greatly on the overall energy and emissions picture. There may be much which can be learned from uptake and usage patterns of the recent large scale adoption of other technologies such smartphones, particularly with user groups who are usually more technology averse.

The System Dynamics model has been used to generate three scenarios to illustrate some possible outcomes for AV usage. Despite the large uncertainties surrounding the multiplicative assumptions used to generate the model structure and it outputs, the model helps to gain a sense of proportion by lifting static data from tables and combining it in a single place. It is postulated (from Scenario 2) that without much intervention and direct connected traffic management (using either a cooperative approach or an outright higher authority to directly control the progression of vehicles) that traffic volumes will continue to increase, but the potential corresponding emissions increase will be at least partially offset by traffic efficiency improvements due to automation. From Scenario 3 we can see a significant net improvement due to the coupling of increased traffic to the use of ULEVs in place of their ICE counterparts. This is combined with a better end-to-end journey experience for those still making longer journeys by road experiencing fewer delays and contributing fewer emissions as a result. If higher levels of automation are restricted from use by governance or the technological and regulatory challenges are not met, then we are left with a plateaux resulting in only modest improvements to emissions. This is described by Scenario 1 or even the pessimistic outcome of Scenario 0 where ADAS features do not advance further or find deeper market penetration away from premium vehicles and throw-away sales incentives for cheaper vehicles as the existing technology matures.

5 Further Work

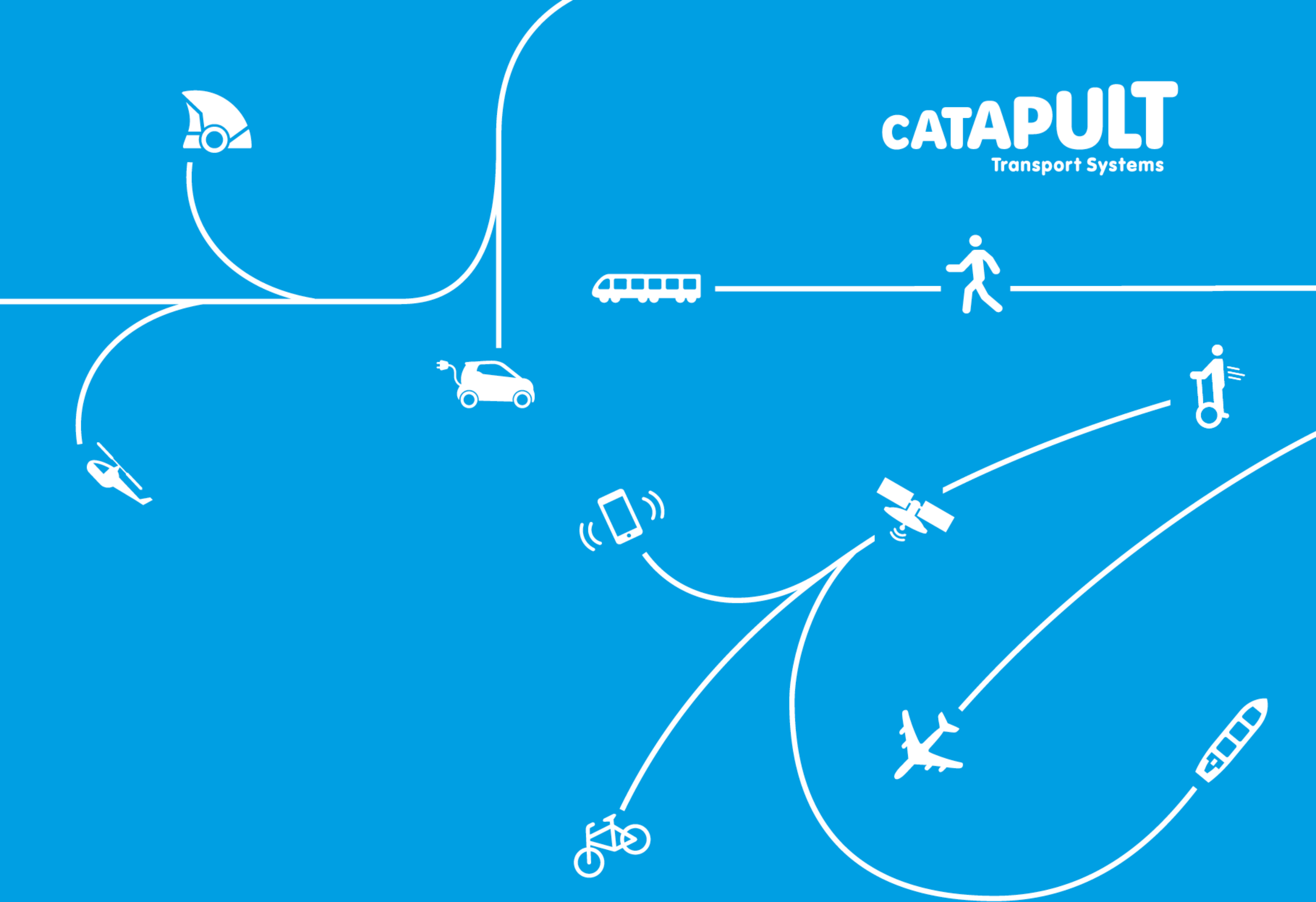
The aim of the modelling exercise in this project was to help in understanding the relationships between factors affected by CAV technologies and affecting energy consumption and emissions in road transport. This has been achieved through the process of building the model and using it to explore potential scenarios. However, there is much more work which could be done to expand understanding and eventually support policy decisions in this area.

The TSC is not planning a direct follow-on project to this modelling exercise. This is because, having shown some of the potential of such a tool, the next step is to use it to answer specific questions that policy makers, transport planners or others have. The TSC therefore plans to talk to potential users of the model, including local authorities, universities and government departments, to explore the potential questions they are interested in. In order to answer specific questions, relevant data would need to be available, and the model would have to be tailored appropriately. The scope of the model could also change, for example looking at a smaller geographical region than the whole of the UK. This could be helpful for a local authority or transport planner. For example, Transport for London (TfL) may be interested in looking at relationships between certain factors for transport in London. This would mean the data used in the model would all be related to London, and the model could be adapted to use the information which TfL already collects and highlight areas in which more data collection would be beneficial.

As well as further modelling work, there is also the potential for further work in using the model in its current state, mainly as a communication tool. As stated in the Methodology section, System Dynamics models can help with framing, understanding, and discussing complex issues which occur at the societal level. The visual nature of the model as represented in Stella Professional enables causal relationships to be easily discussed and debated at any level of detail. This type of discussion could provide valuable insight for policy makers.

The model can also be used via visual communication to inform other modelling exercises by highlighting the issues and interconnections which may need to be considered. This will be trialled in the first instance with the TSC's Modelling and Visualisation team, who generally work on agent-based transport modelling, as they are looking into the areas of AVs and emissions as part of their 2016/17 work plan. The TSC is also interested in further collaboration with the DfT where insights could be used to support development of the NTM or other projects.

Finally, as discussed in the Data section, one of the main limitations to the power of any model is the appropriateness and richness of the data behind it. This modelling exercise therefore also helps to highlight areas in which further data collection and research (academic and industrial) could provide useful insights for the UK.



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