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of Connected & Autonomous vehicles

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D7.4 – Long term impact analysis with a system-dynamics model

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List of acronyms	
Acronym	**Meaning**
ABM	Agent-Based Model
CAV	Connected and Autonomous Vehicle
DOI	Diffusion of Innovations
EV	Electric Vehicle

ICE	Internal Combustion Engine
IoT	Internet of Things
R&D	Research and Development
SD	System Dynamics
VMT	Vehicle Mile Travelled
WP	Work Package

Notice

This document was drafted based on the European Blind Union’s guidelines (http://www.euroblind.org/publications-and-resources/making-information-accessible-all) in order to be accessible to anyone, including blind and partially sighted people, and at the same time and at no additional cost.

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Executive summary

The aim of PAsCAL is to develop a holistic, user-centric Guide-to-Autonomy concept aimed at accelerating the user-friendly evolution of connected and automated vehicles (CAVs) and transport systems. In doing so, it addresses important issues relating to the role of humans in this evolution, ranging from real-time driving control to long-term training needs for jobs, in particular appropriate interactions of the autonomous vehicles with different road users including disabled people and non-drivers.

PAsCAL carried out a set of thorough surveys (e.g. online, face-to-face interviews) on public acceptance (WP3), simulated driving scenarios (WP4), training and education (WP5), and real-world demonstrations (WP6). WP7 brought together the results from all these previous WPs and carried out a systematic and detailed analysis of user behaviour, and assess the potential impacts of various levels of user acceptance on CAVs, and support decision makers in considering the pros and cons of future CAV solutions.

With impact areas and pathways of CAVs identified in D7.1, impact indicators reviewed in D7.2, and knowledge inputs on user acceptance from D7.3 and WP3, **this deliverable (D7.4) represents work carried out in Task 7.4** in which a System Dynamics (SD) based model was developed to simulate the diffusion of CAVs and its impacts over a 50-year period, using the UK as a case country, to explore how users' perception, CAV technological advance and CAV utilities affect user acceptance and CAV diffusion, the wider mobility and society impacts of CAV diffusion, and the dynamic relationships between all these factors.

The SD model adopted Bass innovation diffusion theory which considers two types of acceptance, driven by desire to innovate and by need to imitate the rest of the society. CAVs in three modes were considered: CAV private car, CAV car/ride sharing and CAV bus, and potential users who accept CAVs will choose between them. Key CAV diffusion indicators calculated in the SD model include CAV technology advance, number of CAV users, CAV fleet size and CAV market penetration. The model also calculates indicators that reflect wider impacts of CAVs. Key CAV impact indicators include average travel time, average travel cost, mode share, Vehicle Miles Travelled (VMT), energy intensity, carbon emissions, and traffic accidents. Six scenarios, i.e., marketing campaign, training campaign, Research and Development (R&D) investment increase, CAV overall boost, CAV shared mobility boost and CAV public transport boost,

in additional to a base scenario, were tested, to assess the long-term impacts of possible interventions that are designed to stimulate CAV diffusion and to optimise CAV impacts.

The results suggest that without interventions CAV diffusion will be slow in the beginning and then start to increase rapidly from around 2035. After an S-shaped growth it will reach market saturation of 98% in around 2057. CAV diffusion will lead to reductions in average travel time, average travel cost, carbon emissions and traffic accidents.

Training campaign, which prepares people to be ready for CAVs when they need to imitate existing users, is more effective in accelerating CAV diffusion than marketing campaign, which encourages innovators and early adopters to adopt CAVs out of their desire to innovate. Promoting shared CAVs and CAV public transport can contribute to more sustainable and more affordable mobility with CAVs, although this may lead to smaller CAV market size in terms of CAV sale.

The results were used to develop policy recommendations which will feed into the Guide2Autonomy in WP8.

1 Introduction

1.1 Purpose and organisation of the document

Connected and autonomous vehicle (CAV) is becoming a reality after a rapid acceleration in investment and development over the past decade. Level 1 and Level 2 driving automation, defined by SAE International (2021), have already been available in the market for several years, and recently, some Level 3 systems have been delivered to the market. In 2020, Waymo launched its Level 4 driverless taxi service in the suburbs of Phoenix, US. However, market-ready technologies for high level automation remain scarce, and wide diffusion of Level 4 and Level 5 CAVs are still decades to come (Litman, 2021).

The diffusion of CAVs over time will depend on many technological, marketing and policy factors. Extensive research has been done to simulate possible diffusion scenarios, predict their timings, and explore how policy makers and industry professionals can provide supports to stimulate the diffusion (e.g., Nieuwenhuijsen et al., 2018; Shabanpour et al., 2018; Talebian & Mishra, 2018). However, most of these studies focused only on private CAVs, while shared CAVs and CAV public transport are also expected to be important. Moreover, few of these studies considered the impacts that the resulted CAVs diffusion would have on the road networks and the wider society.

On the other hand, the impacts of CAVs are uncertain. The directions and extents of CAV impacts can be very different, even opposite, and will very much depend on the choice of CAV modes. For example, wide use of private CAVs may lead to higher car dependency and hence more congestion and pollutions (Auld et al., 2017; Kim et al., 2015), while shared CAVs and CAV public transport have higher potential for mobility equity and sustainability (Abe, 2019; Krueger et al., 2016; Pigeon et al., 2021). These impacts can also in return affect CAV diffusion.

Therefore, this document (D7.4) aims to provide a System Dynamics (SD) based model to simulate the diffusion of CAVs in the UK over a long period from 2020 to 2070. It will allow to explore and gain insights into how users' perception, CAV technological advance and CAV utilities affect user acceptance, mode choice and CAV diffusion, the wider mobility and society impacts of CAV diffusion, and how these in return influence users' perception, CAV technological advance and CAV utilities. The model will utilise a list of indicators that were reviewed and suggested in D7.2, and test a range of scenarios to assess the long-term impacts of policies, interventions and CAV solutions that are designed to stimulate the diffusion of CAVs and to enable the successful transition to a fully connected and automate transport system.

Following Chapter 1 Introduction, the remaining of the document consists of:

Chapter 2, a review of innovation diffusion and CAV diffusion studies, in particular, studies using SD modelling, which provided the theoretical and methodological foundations for this study;

Chapter 3, development of scenarios and selection of indicators to be tested in this study, to guide the design of the model;

Chapter 4, description of the model structure, components, and details of the equations and constants;

Chapter 5, presentation of the simulation results of CAV diffusion and CAV impacts, compared between different scenarios;

Chapter 6, a summary of the results, and based on the results, policy recommendations for accelerating CAV diffusion and optimising CAV impacts;

Chapter 7, conclusions of the study with caveats.

1.2 Intended audience of this document

The main audience for this document is the consortium partners of the PAsCAL project, in particular, partners who are responsible for developing guidelines and recommendations in WP8 for different stakeholders (e.g., policy makers, service providers, manufacturers and users) regarding CAV acceptance, diffusion and impacts. The document will provide them a better understanding of the long-term impacts of different CAV policies, interventions and solutions. This can also help policy makers to achieve better decision-makings. The document will also benefit the wider research communities, by contributing new knowledge on the dynamics between CAV user acceptance, CAV modes, CAV diffusion and their wider impacts.

2 Literature Review

Many studies have explored or forecasted the diffusion of CAVs. Some of them used different terminologies such as CAV adoption, deployment, uptake, market penetration, etc., but in general they are all diffusion of CAVs over time. While some of them were based on methods such as historical analogies, expert interviews, panel consensus, trend projections and scenario development (Nieuwenhuijsen et al., 2018), many others used quantitative modelling methods which are less biased and are able to address complex issues over the diffusion process using a more systematic approach. This review will focus on quantitative modelling studies on CAV diffusions, in particular, system dynamic modelling.

2.1 Diffusion of Innovations and CAV diffusion

Since CAV is an innovation in transport system, a large part of the CAV diffusion literature was based on the theory of Diffusion of Innovations (DOI). DOI is the process by which “an innovation is communicated through certain channels over time among the members of a social system” (Rogers, 2010, p5). The innovation can be an idea, practice or product that is perceived as new by the members. Since the seminal study on the diffusion of hybrid seed corn among Iowa farmers in 1943 (Ryan & Gross,1943), DOI has been applied in a wide range of fields such as marketing, education, medicine, energy, etc. (Meade & Islam, 2006; Rogers, 1976). Modelling and forecasting methods for DOI have been continuously developed, adding more flexibility and improving accuracy to the main models that were developed before 1970 (Meade & Islam, 2006).

A widely used DOI model is the Bass diffusion model (Bass, 1969). The Bass model describes the process of how an innovation is adopted by new users either as innovators or as imitators. Innovators adopt the innovation because of their desire to innovate, and their adoption rate is influenced by advertising effect; while imitators adopt the innovation because of the need to imitate the rest of the society, and their adoption rate is influenced by word-of-mouth effect, i.e., their contacts with existing users. Equation (1) gives the basic model formulation of Bass model, which leads to an S-shaped curve of cumulative number of adopters over time.

$$f(t) \,/\, (1 - F(t)) = p + qF(t) \qquad (1)$$

where:

- *F(t)* is the cumulative adopters (as a fraction of the total potential market) at time *t*
- *f(t)* is the new adopters (as a fraction of the total potential market) at time *t*
- *p* is the coefficient of innovation
- *q* is the coefficient of imitation

The advantages of Bass model are that it considers the influence of market size and user behaviour, and the coefficients can be calibrated using real-world data or historical data of diffusions of similar innovations, which can also be updated easily when better data or knowledge become available (Lavasani et al., 2016).

The Bass model has been applied to study innovation diffusions in various areas such as consumer durable goods, retail services, agriculture, education, etc. (Mahajan et al., 1990), and extensions were made to account for issues such as pricing, competition among companies and successive product generations (Krishnan et al., 1999; Maier, 1999; Michalakelis et al., 2010). Some studies also integrated Bass model into system dynamic modelling to address dynamics in the diffusion process. These studies will be reviewed in Section 2.2.

There is currently a very limited body of literature on CAV diffusion using Bass model. Lavasani et al. (2016) used a generalised Bass model, the basic model with extension of pricing and economic wealth effects, to estimate market penetration of CAVs in the US. Since no CAV sale data was available, historical sale data of electric vehicles (EV) in the US was used to estimate the model, with the assumption that market penetration pattern of CAV would be similar, and with adjustment using Internet and cell phone adoption data. After comparing the coefficients of innovation (*p*) and coefficients of imitation (*q*) of the diffusions of conventional internal combustion engine (ICE) cars, EVs, Internet and cell phone, the study suggested a value of 0.001 for the *p* and a value of 0.341865 for the *q* for CAV diffusion. The estimated coefficients for the extended pricing (as price ratio of an EV compared to an ICE counterpart) and economic wealth effects were −1.314 and 8.913, respectively. However, it is not clear how the economic wealth effect variable was calculated in this study. Using the resulting model, the study forecasted that the US CAV market will be saturated by around 2060 and approximately 87 million CAVs will have been sold by then. Given that the number of households in the US used in this study was 116 million, the forecasted market penetration rate of

75% was in a similar range to those reported in other studies (Litman, 2021; McKinsey & Co., 2016).

Shabanpour et al. (2018a) modelled adoption timing of CAVs in the Chicago metropolitan area using a Bass model. They extended the Bass model so that individuals' innovation/imitation desires are heterogeneous depending on their socio-demographic characteristics, attitudes towards CAVs and land use patterns associated with them, i.e., the values of *p* and *q* are functions of these individual characteristics variables. An online stated preference survey was conducted to obtain data to estimate the extended Bass model. The results show that being higher educated, part of a couple, a frequent long-distance traveller, and paying parking cost at work increase the *p* value, while being CAV stressful and senior with good access to transit reduce *p* value; and having experience of an accident increases *q* value, while being part of a couple, a frequent long-distance traveller and willing to accept higher additional cost for CAVs reduce *q* value. The average *p* value and *q* value were 0.108 and 0.957, which are much higher than those in Lavasani et al. (2016) especially the *p* value. Using the estimated model, it was forecasted that the likelihood of an average resident of the Chicago metropolitan area to eventually adopt a CAV is 71.3%. However, the timing can be very different between individuals. Those with max *p* value and *q* value could reach 100% probability of adoption by around 2042, while those with min *p* value and *q* value could only reach approximately 10% probability of adoption by 2042, and still less than 60% by 2070 which is the end of the study time period.

Talebian et al. (2018) also considered individual heterogeneity when forecasting CAV adoption among employees of the University of Memphis, by integrating the Bass model with an agent-based model (ABM). In their ABM, an individual decided to adopt CAVs when (i) needed a new vehicle; (ii) WTP was greater than CAV price; and (iii) overall impression about CAVs reached a cut-off value. Individuals' WTP and overall impression about CAVs changed over time based on media exposures and peer-to-peer communications. A survey (N=327) was conducted among employees of the University of Memphis to obtain data on WTP and CAV perception of individuals of different socio-economic characteristics, their social networks, and their considered reliability of media and peer-to-peer communications. The survey data was also used to generate a synthetic population for ABM. Given additional cost of full automation is $40,000 at the base year, the results show that with a 5% annual cost reduction rate, only 15% of the University employees will adopt CAVs by 2050. However, the adoption rate can increase to 90% with a 20% cost reduction rate. Changing model parameters that reflect intensity of marketing shows that pre-introduction marketing did not change the adoption timing and rate, while post-launch marketing enhanced adoption but the effect was capped.

2.2 System dynamics modelling and applications in CAV diffusion

Traditional DOI models including Bass models have some limitations. Many variables that can influence adopter decisions, such as product price and quality, are added as exogenous inputs into the models, and there is no feedback from adoption results to these variables (Maier, 1998). However, in reality, management decisions on capacity, pricing, quality control, etc. are often made dynamically in accordance with market demand, to maximise market penetration and profit. The adoption results may also affect other factors that can change adoption decisions but beyond the control of product manufacturers or service providers, e.g., land use changes and transport network performance in the case of CAVs.

System Dynamics (SD) can improve the models by adding dynamic feedback loops between these interactive components in the complex innovation diffusion system. SD is a method to describe, model, simulate and analyse dynamic feedback systems (Pruyt, 2013). It has been developed since the pioneering work of Forrester (1961), and it is the application of system control principles and techniques to the studies of organizational, social, economic and/or environmental problems (Forrester, 1961; Pruyt, 2013).

Early applications of SD to innovation diffusion modelling can be found in Milling (1986; 1996), where feedback loops were established, based on the core structure of the Bass model, between probability of adoption (or in other words, market demand and sales) and management decision variables and cost reduction via experience curve. Since then, SD has been applied in innovation diffusion in a wide range of fields, e.g., renewable energy (Markard et al., 2016), food industry (Horvat et al., 2020), mobile apps (Harrison, et al., 2020), and electric vehicles (Santa-Eulalia et al., 2011; Shepherd et al., 2012; Struben & Sterman, 2008).

Within the limited body of literature on CAV diffusion, Nieuwenhuijsen et al. (2018) applied SD. In this study, five interactive components of the CAV diffusion system were identified: (1) technology maturity, (2) purchase price, (3) perceived utility, (4) fleet size, and (5) car carsharing demand. The system was dynamic that technology maturity reduced purchase price and increased perceived utility, which stimulated sale and increased fleet size. The growing market fed back to Research and Development (R&D) investment which enhance technology maturity. The technology maturity also affected car sharing demand which could reduce fleet size. Using the Netherlands as a case study, the results show that Level 3 vehicles start to replace Level 1and 2 from 2020, and become dominant in the total fleet from around 2050. Growths of Level 4 and 5 vehicles remain slow throughout the modelling period and together only reach 34% of the total fleet around 2100. While fleet size of Level 4 and 5 remain growing steadily, the total fleet size starts to decrease from around 2050, due to the rise of carsharing. The study also tested scenarios that stimulate CAV adoption, where different values for parameters such as price impact on perceived utility, R&D investment, subsidies for CAVs were tested. In these scenarios, CAV adoption was significantly enhanced, with Level 5 vehicles reach as high as 99% of total fleet around 2100. However, the study did not consider impact of CAV usage on road network performance and social and environmental impacts which could feed back to perceived utility and car sharing demand, and change the dynamics of the diffusion system.

Built on the model developed by Nieuwenhuijsen et al. (2018), Harrison et al. (2018) explored sensitivities of adoption to utility for Level 4 & 5 CAVs, and extended the model to explore how internet of things (IoT) based technology services, including alerts of upcoming hazards on motorways, matching users wishing to platoon, connections to more devices for urban driving, could accelerate CAV adoption. Their results show that adoption of Level 4 & 5 CAVs are most sensitive to the weighting of attractiveness in the utility function, and the levels of safety and comfort. Utility provided by the added IoT based technology services could contribute to a higher market share of Level 4 & 5 CAVs.

Instead of modelling the diffusion process, some studies used SD to model the impacts of CAV diffusion on the mobility system over time. With assumed penetration rates of Level 1, 2 & 3 vehicles over time as exogenous inputs, as well as assumed car capacity, value of time and monetary costs associated with these vehicles, Puylaert et al. (2018) modelled impacts of vehicle automation on modal split, numbers of people traveling by car in peak hours and car travel times between different areas in the Netherlands from 2010 to 2050. Results show that vehicle automation would increase car trips as well as trip lengths, and increase congestion on some trip types. With an assumed increase curve of CAV fleet share over time, May et al. (2020) used an SD Land Use – Transport Interaction Model to simulate impacts of CAV diffusion on travel demand, travel behaviour and residential distribution in Leeds, UK. The results show that CAV adoption leads to higher car-km and person-km, and reduced public transport use, walking and cycling. Private ownership of CAVs will also contribute to urban sprawl while shared ownership could encourage more compact development.

3 Scenario development

3.1 User acceptance

Level of user acceptance can influence the rate of CAV diffusion. Both user attributes and vehicle/system attributes can affect level of user acceptance. User attributes include demographic attributes such as age, gender, education and income (Jing et al., 2020; Othman, 2021); and psychological attributes such as technological motivation, environmental concern, personal and social norms (Buckley et al., 2018; Haboucha et al., 2017). Vehicle/system attributes include cost such as purchase cost, usage cost, tax and insurance (Chen et al., 2019; Shabanpour et al. 2018b); and functions such as usefulness (e.g., travel time saving), ease of use, safety and privacy (Kaur & Rampersad, 2018; Liljamo et al., 2018)

From CAV diffusion strategy perspective, user acceptance can be enhanced by improving user psychological attributes and vehicle/system cost and function attributes. Table 3.1 lists examples of potential instruments for such improvements.

Table 3.1: Instruments to enhance user acceptance

Instrument categories	Instruments	user psychological attributes	Vehicle/ system cost attributes	Vehicle/ system function attributes
Marketing	Advertisement of CAVs	Technological motivation, environmental concern	-	-
	Free trial of shared CAVs or CAV transit	Trust, familiarity	Lower cost	-
	Regular media presentations of CAVs	Social norm	-	-
Training	New driving training programmes and tests (especially for Level 3)	Trust, familiarity	-	-
	Education campaigns (automation features, traffic rules, etc)	Trust, familiarity	-	-

Instrument categories	Instruments	user psychological attributes	Vehicle/ system cost attributes	Vehicle/ system function attributes
R&D	Investment to advance technology	-	Lower cost	Ease of use, usefulness, safety, security
	Vehicle and system design for the needs of disabled and vulnerable users	-	-	Ease of use, usefulness
	Innovative and Enhanced Cybersecurity Risk Assessment and Protection	-	-	Safety, security
	Standardisation of Human-Machine Interfaces	Familiarity	-	Ease of use
Operation, service and business model	On-demand CAV service	-	-	Usefulness
	Service design for the needs of disabled and vulnerable users	-	-	Ease of use, usefulness
	Make revenue from data generated by CAVs	-	Lower cost	-
Traffic rule	Safe and clear interaction between CAVs and other road users	Trust	-	Safety
	CAV dedicated lanes (for Level 3 & 4)	-	-	Ease of use, safety
Subsidy, tax and insurance	Subsidy for shared CAV services	-	Lower cost	-
	Lower tax and insurance on CAV private cars	-	Lower cost	-
Legislation and regulation	Enhanced Privacy Protection and Data Storage Protocols	Trust	-	Privacy
	Clarity and uniformity of liability	Trust, familiarity	-	Ease of use

3.2 CAV impacts

CAVs will not only change the mobility of the individual users, but also have wider impacts on the mobility system, and environmental and socio-economic impacts on the society. Potential mobility impacts include impacts on e.g. travel demand, congestion, mode share, traffic accidents, accessibility (Harper et al., 2016; Luttrell et al., 2015; Stanek et al., 2017; Soteropoulos et al., 2019). Potential environmental impacts include impacts on e.g. energy efficiency, carbon emission, air pollution, noise, land use (Rojas-Rueda et al., 2020; Stead & Vaddadi, 2019; Wadud et al., 2016). Potential socio-economic impacts include impacts on e.g. mobility equity, labour market, government revenue from tax, local business and economic development (Nikitas et al., 2021; Sparrow & Howard; 2020; Terry & Bachmann, 2019).

These impacts, as consequences of CAV adoption, are important indicators to assess the success of CAV development and deployment. Many of them can also in return affect people's attitudes towards or preference of CAVs and hence adoption rate. However, the directions and/or extents of these impacts are still uncertain, and many will depend on the modes of CAVs, e.g., private CAVs VS shared CAVs (May et al., 2020; Soteropoulos et al., 2019). Table 3.2 lists examples of potential instruments that can optimise these impacts

Table 3.2: Instruments to optimise CAV impacts

Instrument categories	Instruments	Mobility impacts	Environmental impacts	Socio-economic impacts
Training	Reskilling programmes ahead of envisaged employment impacts CAVs	-	-	Labour market
R&D	Investment to advance technology	Congestion, traffic accident	Energy efficiency, carbon emission	-
	CAV industry and business to support local economy	-	-	Business development, economic development

Instrument categories	Instruments	Mobility impacts	Environmental impacts	Socio-economic impacts
	Make CAVs environmentally friendly by design	-	Energy efficiency, Carbon emission, Air pollution, etc.	-
	Vehicle and system design for the needs of disabled and vulnerable users	Accessible mobility	-	Equity, inclusion and diversity
Operation, service and business model	CAV services and job creation	-	-	Labour market
	Service design for the needs of disabled and vulnerable users	Accessible mobility	-	Equity, inclusion and diversity
	Integrate shared CAVs with public transport	Mode share, congestion	Carbon emission	Social equity
	Make revenue from data generated by CAVs	-	-	Business development
Traffic rule	Safe and clear interaction between CAVs and other road users	Traffic accident	-	-
Subsidy, tax and insurance	Higher tax on private CAVs	Mode share, congestion	Carbon emission	Government revenue
	Subsidy for shared CAVs and public transport	Mode share, congestion	Carbon emission	Social equity

3.3 Scenarios and indicators to test

This study uses an SD model to explore CAV diffusion over time. It will quantify long term impact of different forms and rates of user acceptance on diffusion, and assess interventions on technology and service development in a set of scenarios.

Two forms of user acceptance are modelled, which are the desire to innovate and the need to imitate the rest of society as described in Bass model in Section 2. Their rates can be affected by marketing and training via the impacts on user psychological attributes. Technology development, which can also enhance the user acceptance rate by improving vehicle/system attributes, as well as affect CAV impacts, can be boosted by R&D investment. Service development in the form of different CAV modes, which can substantially affect CAV impacts, can be promoted by supportive regulations, subsidies, operation strategies, etc.

Corresponding to these, six scenarios, in additional to a base scenario, were developed:

- Marketing campaign: more marketing activities to promote the exposure and attractiveness of CAVs to the public, in particular, to the innovators and early adopters.
- Training campaign: more training activities to enhance people’s familiarity to CAVs and confidence in using them, when they need to follow the rest of the society.
- R&D investment increase: more R&D investment to accelerate CAV technology development.
- CAV overall boost: policy interventions to support the use of all CAVs, e,g., subsidies and road priority for all CAV use, aiming to stimulate the diffusion of all CAVs regardless of mode.
- CAV shared mobility boost: policy interventions to support the use of shared CAVs and CAV public transport, e,g., subsidies and road priority for their use, aiming to stimulate the diffusion of shared CAVs for sustainability.
- CAV public transport boost: policy interventions to support the use of CAV public transport, e,g., subsidies and road priority for its use, and discourage the use of private CAVs, aiming to stimulate sustainable diffusion of CAVs in a more radical approach.

Table 3.3 lists the seven scenarios and changes in some model variables that reflect interventions taken in each scenario. The model variables will be explained in Section 4.

Table 3.3: Scenarios to be tested as changes in relevant model variables.

	Marketing	**Training**	**R&D investment**	**CAV private car travel cost**	**CAV private car travel time**	**CAV car/ride sharing travel cost**	**CAV car/ride sharing travel time**	**CAV bus travel cost**	**CAV bus travel time**
Base	0	0	0	0	0	0	0	0	0
Marketing campaign	1	0	0	0	0	0	0	0	0
Training campaign	0	1	0	0	0	0	0	0	0
R&D investment increase	0	0	+£1200 million / year	0	0	0	0	0	0
CAV overall boost	0	0	0	-£0.5 / trip	-1.5 min / trip	-£0.5 / trip	-1.5 min / trip	-£0.25 / trip	-5 min / trip
CAV shared mobility boost	0	0	0	0	0	-£3 / trip	-2 min / trip	-£0.5 / trip	-10 min / trip
CAV public transport boost	0	0	0	+£2 / trip	+3 min / trip	0	0	-£1 / trip	-15 min / trip

Indicators calculated in the model to assess the success of CAV diffusion and effectiveness of interventions include CAV technology advance, number of CAV users, CAV fleet size and CAV market penetration. The model also calculates indicators that reflect wider impacts of CAVs. These indicators include average travel time, average travel cost, mode share, Vehicle Miles Travelled (VMT), energy intensity, carbon emissions, and traffic accidents, which are related to the Sustainable Urban Mobility Indicators developed by European Commission (2020), e.g., affordability of public transport, road deaths, greenhouse gas emissions, congestion and delays, energy efficiency, and commuting travel time. Table 3.4 lists the indicators and the calculations are detailed in Section 4.

Table 3.4: Indicators of CAV diffusion and CAV impacts calculated in this SD model.

CAV diffusion indicators	CAV impact indicators
CAV technology advance	Average travel time
Number of CAV private car users	Average travel cost
Number of CAV car/ride sharing users	Percentage of private car users (including non-CAV private car users) in total population
Number of CAV bus users	Percentage of bus users (including non-CAV bus users) in total population
Number of CAV users	Vehicle mile travelled
Percentage of CAV users in total population	Energy intensity
Fleet size of CAVs	Carbon emission
Fleet size of total vehicles	Traffic accident
Percentage of CAVs in total vehicle fleet	

4 The System-Dynamics (SD) model

4.1 Model overview

The SD model of CAV diffusion developed in PAsCAL uses the Bass model as the core structure, with extensions to include three modes of CAVs: CAV private car, CAV car/ride sharing and CAV bus, and impacts of CAV diffusion on mobility which feeds back to CAV adoption and mode choice. Figure 4.1 shows the overview of the SD model with key components.

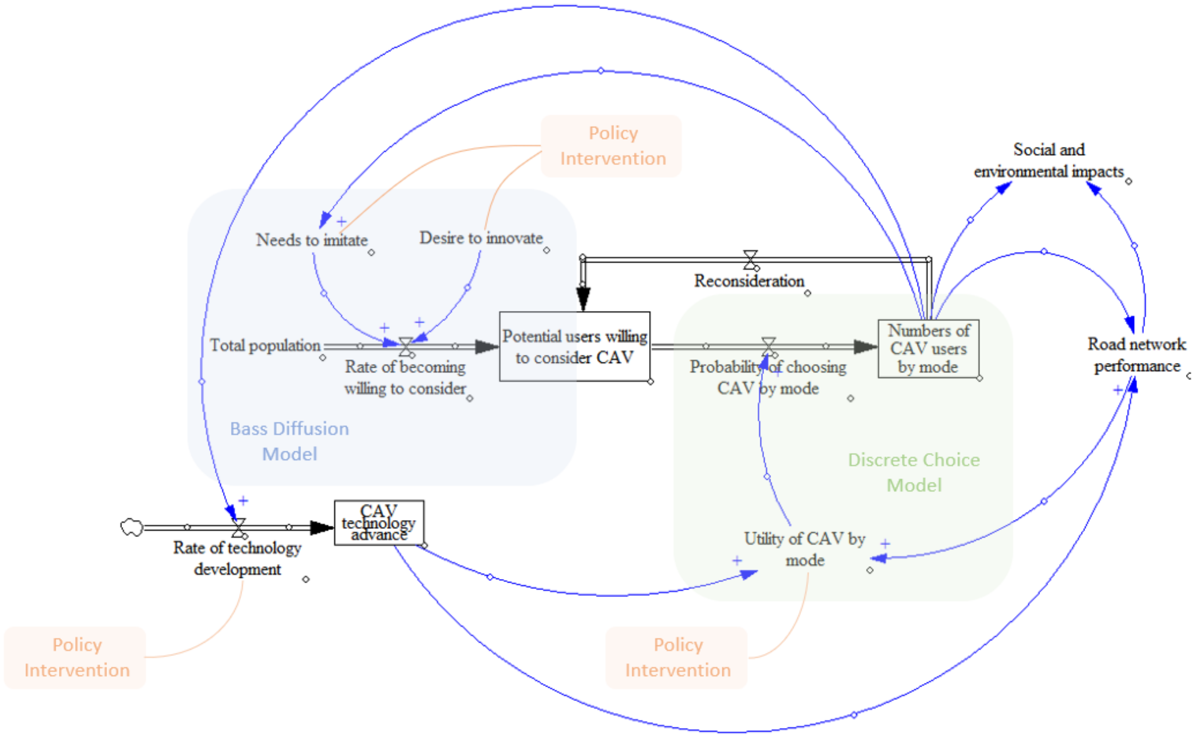

Figure 4.1: Overview of the SD model with key components.

In this model, potential users become willing to consider CAVs by the desire to innovate, and by the need to imitate others. Those who are willing to consider CAVs will choose between CAVs of different modes or remain the choice of non-CAV, depending on the utility of each option, considering travel time and travel cost. Every certain time periods, users of each mode will reconsider their choices. Number of users of each mode hence increases with adoption and decreases with reconsideration. Utility of each mode is influenced by CAV technology advance and road network performance. CAV technology advances accumulate overtime, and the rate is influenced by CAV market size, i.e., number of CAV users. Road network performance is influenced by CAV technology advance, and travel behaviour which is determined by number of users of each mode. Environmental impacts of CAV uptake can also be calculated based on road network performance and number of users of each mode. With this model, policy interventions can be tested by adding them as exogenous inputs to change rate of willingness to consider CAVs (e.g., marketing), rate of technology advance (e.g., R&D investment), and utilities of different modes (e.g., subsidies).

The model was implemented in Vensim DSS. The time step for simulation was 1 year and the time horizon was from 2020 to 2070. The UK was used as the case country and its population of 67.22 million in 2020 (World Bank, 2022) was used as the total population in the model. The reason to use a single country was to facilitate modelling within a homogeneous context and with consistent data for assumption development. The result implications however would be relevant for other countries and wider regions. Focusing on a single country or city is also the approach used in many other CAV and EV diffusion modelling studies (e.g., Lavasani et al., 2016; May et al., 2020; Nieuwenhuijsen et al., 2018; Shabanpour et al., 2018a; Shepherd et al., 2012). Population growth was not modelled so effects of CAV diffusion on total number of CAV users, total fleet size, total carbon emission, etc. can be more easily traced over time. The model does not include freight transport. The following sub sections describe the model in more detail in relation to the key components, equations and constants. Full lists of model equations and constants are also provided in Appendix.

4.2 Innovation diffusion

The innovation diffusion component of this SD model used the Bass diffusion model (Bass, 1969) which was reviewed in Section 2.1. At the start of the simulation period which is the year 2020, potential users who are not yet willing to consider CAV are the total UK population which is 67.22 million. Over time, they become willing to consider CAV because of their desire to innovate or because they want to imitate the others who are already using CAVs. The innovation coefficient p of 0.001 and imitation coefficient q of 0.341865, estimated for CAV diffusion by Lavasani et al. (2016) , are used in this model. Given Equation 1 in Section 2.1, the coefficient p means every year, 0.1% of the potential users who are not yet willing to consider CAVs become willing to consider by innovation;

while the coefficient q means every year, (34.1865 × number of CAV users ÷ total population)% of the potential users who are not yet willing to consider CAVs become willing to consider by imitation.

We assume both the innovation effect and imitation effect can be enhanced by up to 30% by CAV technology advance, as a result of overall improvement on e.g. perceived safety, perceived usefulness, perceived ease of use brought about by technology advance. We further assume the innovation effect can be enhanced by up to 30% by marketing, e.g., through advertisements innovators become more aware of or more interested in CAVs; and the imitation effect can be enhanced by up to 30% by training, e.g., after training imitators become more confident in using CAVs and hence more likely to try them to following other users. To include these enhancing effects we added equations:

$$\text{innovation effect} = \text{coefficient}\, p \times (1 + 0.3 \times \text{marketing} + 0.3 \times \text{CAV technology advance}) \tag{2}$$

where CAV technology advance is a dimensionless variable with 0 means no CAV technology and 1 means the most advanced technology achievable (see Section 4.5), and marketing is a dimensionless variable of marketing activity intensity, with 0 means no marketing activity and 1 means maximum marketing activities.

$$\text{imitation effect} = \text{coefficient}\, q \times (1 + 0.3 \times \text{training} + 0.3 \times \text{CAV technology advance}) \tag{3}$$

where training is a dimensionless variable of training activity intensity, with 0 means no training activity and 1 means maximum training activities.

4.3 User choice

Potential users who are willing to consider CAV will choose from CAV private car, CAV car/ride sharing and CAV bus, or remain the choice of non-CAV. They become users of these three CAV modes respectively, or remain potential users who are willing to consider CAV in the case of choosing non-CAV. Their choices will depend on the utility of each option, and the choices are simulated at population level, i.e., percentage of potential users choosing each option at each year. The percentage is calculated using the logit probability equation (Train, 2009):

$$PCT_i = \frac{e^{U_i}}{\sum_j e^{U_j}} \tag{4}$$

where U_i is the utility of option *i* and there are $j = 4$ alternative options.

It is common that every now and then people will change their travel mode. So in this model, we assume that every year, 1% of CAV private car users and 5% of CAV car/ride sharing and CAV bus users will reconsider their choice, i.e., they become potential users who are willing to consider CAV. We choose to use a lower rate for CAV private car users since car owners are less likely to switch between different modes.

Utility of a travel mode can be influenced by travel time, travel cost, comfort, safety, etc (Liu et al., 2019). Due to uncertainty and measuring difficulty in these utility attributes for CAVs, we only consider travel cost and travel time, which are the two highly influential attributes (Hensher & Rose, 2007; Winter et al., 2017), for calculating utility in this model:

$$U_i \;=\; \beta_{tt} \times TT_i \;+\; \beta_{tc} \times TC_i \;+\; ASC_i \tag{5}$$

where TT_i, TC_i and ASC_i are travel time, travel cost and alternate specific constant of option *i*, β_{tt} and β_{tc} are travel time and travel cost coefficients. The ASC represents unobserved preference.

For this model, values of β_{tt} and β_{tc} were assumed based on estimates in Hensher & Rose (2007). For β_{tt}, -0.04 was used considering the range of coefficient values for in-vehicle time, access time and egress time for car, bus and rail reported in their multinomial logit model. Following the same approach, -0.2 was decided for β_{tc}. The units of travel time in both Hensher & Rose (2007) and our SD model are minutes per trip; for unit of travel cost, Hensher & Rose (2007) used US dollar per trip in 2003 value while we use British pound sterling per trip in 2020 value. Considering exchange rate and inflation, 1 US dollar in 2003 is approximately 0.985 British pound sterling in 2020, so we didn't adjust the β_{tc} value for our model.

For ASC_i, 0 was used for CAV private car in our model since car mode was modelled as reference in Hensher & Rose (2007). We then calibrated ASC_i for CAV car/ride sharing and CAV bus, so that the probabilities of choosing CAV private car, CAV car/ride sharing and CAV bus, with travel time and travel cost at their non-CAV counterparts' levels, are the same as the current share of frequent private car users, taxi and car sharing users and bus users in England (see Section 4.4.4). The resulted ASC_i for CAV car/ride sharing is -2.11 and for CAV bus is -1.12. ASC_i for the non-

CAV option is -0.31, which is a weighted-average of the three CAV options. The weighting is explained in Section 4.4.4.

4.4 Travel time and travel cost

Consistent units, minute per trip for travel time and £ (2020 value) per trip for travel cost, are used in our SD model, and we assume a 5-mile distance for all trips. Detailed calculations of travel time and travel cost for the four options are provided in the following sub sections.

4.4.1 Travel time and travel cost of CAV private car

4.4.1.1 Travel time of CAV private car

Travel time of CAV private car includes in-vehicle time and parking time. Given that the average speed on local ‘A’ roads in England in 2019 was 25.3 mph (Department for Transport, 2021a) and our assumed distance of 5 mile per trip, initial in-vehicle time of CAV private car, when traffic congestion is at base level, is 11.86 minutes. As CAV technology advances, CAV market penetration increases and mode share changes, network speed will change which will affect in-vehicle time. Hence the calculation is:

$$CAV\ private\ car\ in\ vehicle\ time\ = 11.86 \times \frac{initial\ network\ speed}{network\ speed} \qquad (6)$$

Calculation of network speed and initial network speed is described in Section 4.6.1.

For parking time, INRIX (2017) reported on average 7.5 min search time for parking in UK. Considering that there is extra time needed for access to and egress from parking space, while return-home trips do not need to search for parking, we assumed 5 minutes for initial parking time per trip. One of the advantages of CAVs is that they don't need to be parked. For example, they can drive themselves to a nearby parking space or back home after dropping off the drivers/passengers at destinations.

However, such use cases will only be possible when technology has reached a certain advance level which we assume to be 0.5 given the 0-1 scale of our CAV technology advance variable.

We also assume on average parking time can only be reduced by up to 80% instead of 100%, since there may still be cases where parking is necessary. Finally, we assume a square root relationship between parking time reduction and technology advance, i.e., marginal time reduction effect decreases as technology advances. Hence the calculation is:

$$CAV\ private\ car\ parking\ time = 5\ \times (1 - CAV\ private\ car\ parking\ time\ reduction) \tag{7}$$

$$CAV\ private\ car\ parking\ time\ reduction = \begin{cases} 0.8\ \times \sqrt{CAV\ technology\ advance},\ if\ CAV\ technology\ advance > 0.5 \\ 0,\ otherwise \end{cases} \tag{8}$$

4.4.1.2Travel cost of CAV private car

CAV private car travel cost consists of car purchase cost and usage cost. According to NimbleFins (2021), average mid-size car price in 2021 in the UK is £23,185. We then assume an initial added cost for vehicle automation of £16,330, converted from the $20,000 in Shabanpour et al. (2018a). This added cost will reduce as CAV technology advances. We use a learning curve to define this reduction effect (Nieuwenhuijsen et al., 2018):

$$CAV\ private\ car\ purchase\ cost = 23185 + 16330\ \times \left(\frac{CAV\ technology\ advance}{initial\ CAV\ technology\ advance}\right)^{-learning\ elasticity} \tag{9}$$

We assume a learning elasticity of 0.5, with which the equation implies that with every doubling of CAV technology advance, the added cost is reduced by around 30%, which is close to the rate of the learning-by-searching curve in Nieuwenhuijsen et al. (2018).

To calculate cost per trip, the purchase cost needs to be divided by the number of trips over a car's lifespan. We assume the lifespan mileage of a typical car to be 200,000 miles (Ford, 2012). Given the trip distance of 5 miles used in this model, the lifespan trip number is 40,000.

For usage cost, average cost to run a car in 2021 in the UK is £1977 per year, considering fuel cost, insurance, tax, repair, etc. (NimbleFins, 2021), and average number of trips per person per year using private car/van as a driver in 2019 in England is 380 (Department for Transport, 2021b). We assume initial CAV private car usage cost is the same as that of conventional car, so we get £5.2 per trip. This usage cost will reduce as CAV technology advances, e.g., by reducing fuel, insurance and maintenance costs (Bösch et al., 2018). Given the estimated reductions in (Bösch et al., 2018), we assume the extent of potential reduction is up to 20%. With the same learning curve as in Equation 9, the calculation is:

$$CAV\ private\ car\ usage\ cost = 5.2\ \times (1 - 0.2\ \times \left(1 - \left(\frac{CAV\ technology\ advance}{initial\ CAV\ technology\ advance}\right)^{-learning\ elasticity}\right)) \tag{10}$$

$$CAV\ private\ car\ travel\ cost = \frac{CAV\ private\ car\ purchase\ cost}{40000} + CAV\ private\ car\ usage\ cost \tag{11}$$

4.4.2 Travel time and travel cost of CAV car/ride sharing

4.4.2.1 Travel time of CAV car/ride sharing

For travel time of CAV car/ride sharing, we use the same speed of 25.3 mph on road as for the case of CAV private car. But instead of parking time, we assume 5 minutes waiting time. Both the in-vehicle time and waiting time will be affected by congestion in the same way as expressed in Equation 6. Only waiting time will be affected by CAV technology advance, e.g., through optimised service planning. Given that waiting time accounts for 30% of the total travel time (5 out of 16.86 minutes), we assume CAV technology advance can reduce up to 20% of the total travel time, and the reduction follows a square root relationship. Hence the calculation is:

$$CAV\ car/ride\ sharing\ \ travel\ time = 16.86 \times \frac{initial\ network\ speed}{network\ speed} \times (1 - 0.2\ \times \sqrt{CAV\ technology\ advance}) \tag{12}$$

4.4.2.2 Travel cost of CAV car/ride sharing

Given Uber’s cost structure of £1.35 base fare, £0.1 per minute and £1.2 per mile (Taxi How Much, 2022), a 5-mile trip with an 11.86 minute trip time would cost £8.536. We use this cost as the initial travel cost of CAV car/ride sharing. This initial cost will reduce as CAV technology advances, and we apply the same reduction rate as expressed in Equation 10 for CAV private car usage cost. However, instead of a 20% reduction extent, we assume a 60% reduction extent for CAV car/ride sharing, since automation can also reduce driver cost and operation cost of car/ride sharing companies.

The initial cost will also reduce as number of users grow. We assume a 25% reduction extent, and a square root relationship between the reduction and percentage of CAV car/ride sharing users among the total population, i.e., marginal cost reduction effect decreases as number of users grows. Hence the calculation is:

$$CAV\,car/ride\ sharing\ travel\ cost = 8.536\ \times \left(1 - 0.6\ \times \left(1 - \left(\frac{CAV\ technology\ advance}{initial\ CAV\ technology\ advance}\right)^{-learning\ elasticity}\right)\right) \times (1 - 0.25\ \times \sqrt{\frac{number\ of\ CAV\ car/ride\ sharing\ users}{total\ population}}) \tag{13}$$

4.4.3Travel time and travel cost of CAV bus

4.4.3.1Travel time of CAV bus

According to the buses performance data from Transport for London (2022), average bus speed in Greater London in 2018/19 was 9.3 mph. Given the trip length of 5 miles, of which we assume 0.5 mile is walk to and from bus stops, initial in-vehicle time of CAV bus is 29 minutes. We assume initial access/egress time for the 0.5-mile walk is 10 minutes, and initial waiting time is also 10 minutes.

Both the in-vehicle time and waiting time will be affected by congestion in the same way as expressed in Equation 6. Both access/egress time and waiting time will be reduced by CAV technology advance, e.g., through optimised service planning and on-demand bus service. We assume the reduction to be up to 50% and follows a square root relationship. Hence the calculation is:

$$CAV\ bus\ travel\ time = 29 \times \frac{initial\ network\ speed}{network\ speed} + 10\ \times \frac{initial\ network\ speed}{network\ speed}\ \times \left(1 - 0.5 \times \sqrt{CAV\ technology\ advance}\right) + 10 \times \left(1 - 0.5 \times \sqrt{CAV\ technology\ advance}\right) \tag{14}$$

4.4.3.2Travel cost of CAV bus

We assume £2 per trip, which is the First Bus single adult ticket for trips within West Yorkshire (UK) in 2021, for the initial travel cost of CAV bus. This initial cost will reduce as CAV technology advances, and we apply the same reduction rate as expressed in Equation 10 for CAV private car usage cost. We assume a 40% reduction extent, which is between the 20% for CAV private car and the 60% for CAV car/ride sharing, since for CAV bus, the reduction from driver cost and operation cost is likely to be smaller than that of CAV car/ride sharing, given the smaller fleet size needed for bus service.

The initial cost will also reduce as number of users grow. We assume a 25% reduction extent, and a square root relationship between the reduction and percentage of CAV bus users among the total population, i.e., marginal cost reduction effect decreases as number of users grows. Hence the calculation is:

$$CAV\ bus\ travel\ cost = 2\ \times \left(1\ - 0.4\ \times \left(1 - \left(\frac{CAV\ technology\ advance}{initial\ CAV\ technology\ advance}\right)^{-learning\ elasticity}\right)\right) \times (1 - 0.25\ \times \sqrt{\frac{number\ of\ CAV\ bus\ users}{total\ population}}) \tag{15}$$

4.4.4Travel time and travel cost of non-CAV option

4.4.4.1Travel time of non-CAV option

We use weighted average of travel times of non-CAV private cars, non-CAV car/ride sharing and non-CAV bus for travel time of non-CAV option[1]. According to Department for Transport (2021c), percentages of frequent private car users, taxi users and bus users were 69%, 2% and 15% in 2019 in England. According to Statista (2021), car-sharing user penetration in the UK is 2.8% in 2021. So the weights we used are 69 : 5 : 15, which are 0.775 : 0.056 : 0.169 when normalised to 1.

For non-CAV private cars, the initial CAV private car in-vehicle time of 11.86 minutes per trip and parking time of 5 minutes per trip (see Section 4.4.1.1) are used, and the in-vehicle time will be affected by network congestion. For non-CAV car/ride sharing, the initial CAV car/ride sharing travel time of 16.86 minutes per trip (see Section 4.4.2.1) is used and it

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[1] Given the much smaller proportions of people who use cycling, walking and/or rail as main travel modes in the UK, and the complications in calculating their utilities, we did not include them when calculating utility of the non-CAV option.

will be affected by network congestion. For non-CAV bus, the initial CAV bus in-vehicle time of 29 minutes per trip, waiting time of 10 minutes per trip and access/egress time of 10 minutes per trip (see Section 4.4.3.1) are used, and the in-vehicle time and waiting time will be affected by network congestion. Hence the calculation is:

$$non\ CAV\ option\ travel\ time = \left(11.86 \times \frac{initial\ network\ speed}{network\ speed} + 5\right) \times 0.775 + 16.86 \times \frac{initial\ network\ speed}{network\ speed} \times 0.056 + \left((29 + 10) \times \frac{initial\ network\ speed}{network\ speed} + 10\right) \times 0.169 \tag{16}$$

4.4.4.2Travel cost of non-CAV option

The weights of 0.775 : 0.056 : 0.169 for non-CAV private cars, non-CAV car/ride sharing and non-CAV bus are used to calculate travel cost of non-CAV option. For travel cost of non-CAV private cars, the conventional car purchase cost of £23,185, usage cost of £5.2 per trip and lifespan trip of 40,000 (see Section 4.4.1.2) are used. For non-CAV car/ride sharing, the initial CAV CS usage cost of £8.536 per trip (see Section 4.4.2.2) is used. For non-CAV bus, the initial CAV bus fare of £2 per trip (see Section 4.4.3.2) is used. Hence travel cost of non-CAV option is calculated to be £5.295 per trip.

4.5 Technology advance

In our SD model, CAV technology advance is a dimensionless variable with 0 means no CAV technology and 1 means the most advanced technology achievable. The technology advance starts from an assumed initial level of 0.1 in 2020 and accumulates overtime depending on the rate of technology development. The rate of technology development is determined by R&D investment and knowledge transfer from investment.

For R&D investment, according to Efrati (2020), at least $16 billion had been spent globally on CAV technology development by 2020. We assume an initial R&D investment of £1.2 billion per year globally, which is approximately $16 billion divided by 10 years using USD/GBP exchange rage in 2021. The investment will increase as market grows, i.e. as number of CAV users increase.

We assume that when market penetration of CAV private car reaches 100%, i.e., when all of the total population become CAV private car users, R&D investment receives an additional £2.4 billion per year, reaching to the highest level of £3.6 billion per year, three times the initial level. Given the larger numbers of users per CAV shared car and CAV bus, we assume that R&D investment increases from their user increases will be smaller than that of CAV private car, and are 1/5 and 1/10 respectively. So when market penetration of CAV car/ride sharing reaches 100%, R&D investment receives an additional £0.48 billion per year, and that for CAV bus is £0.24 billion per year.

We assume these additional investments follow a square root relationship with numbers of CAV users, i.e., marginal investment increase per user reduces as number of users grows.

The R&D investment converts to CAV technology advance through knowledge transfer. We assume the transfer rate to be 0.01 technology advance per billion £ investment. Given the initial and highest possible investment levels of £1.2 billion and £3.6 billion per year, and the highest possible technology advance of 1, this transfer rate configures that technology advance will reach a level between 0.6 and 1 over 50 years in our model.

Finally, the rate of technology development is multiplied by technology gap, which can be expressed as (1 – technology advance). This means that when technology gets more matured, it requires more knowledge to make per unit increase in technology advance (Nieuwenhuijsen et al., 2018). Hence, the calculation is:

$$\begin{aligned}&\mathit{Rate\ of\ CAV\ technology\ development}\\&\quad=\left(1.2+\ 2.4\ \times\ \sqrt{\frac{\mathit{Number\ of\ CAV\ private\ car\ users}}{\mathit{total\ population}}}\right.\\&\quad+0.48\ \times\ \sqrt{\frac{\mathit{Number\ of\ CAV\ car/ride\ sharing\ users}}{\mathit{total\ population}}}\\&\quad\left.+0.24\ \times\ \sqrt{\frac{\mathit{Number\ of\ CAV\ bus\ users}}{\mathit{total\ population}}}\right)\times 0.01\ \times (1\\&\quad-\mathit{CAV\ technology\ advance})\end{aligned} \qquad (17)$$

4.6 CAV wider impacts

4.6.1 Road network impacts

4.6.1.1 Vehicle fleet size

Vehicle fleet size is determined by number of users of each of the four options, i.e., CAV private car, CAV car/ride sharing, CAV bus and the non-CAV option, and number of users that each vehicle can serve in each option.

For CAV private car, according to Department for Transport (2020a), number of cars per household among those with at least one car was 1.59 in 2018/19 in England. Given that the average household size was 2.4 in 2020 in the UK (Office for National Statistics, 2021), we assume each CAV private car, as well as conventional private car, serve 2.4/1.59 which is 1.5 users.

For CAV car/ride sharing, Monitor Deloitte (2017) reported 125 users per car with free-floating car sharing and 45 users per car with stationary car sharing in Germany, and forecasted to have 15.6 million car sharing users and 160k cars to serve them in Europe in 2020, which means 97.5 users per car. These car sharing users are less likely to be frequent car users in the first place, and if CAV car/ride sharing is to replace private cars in the CAV era, the number of users per car might be much lower. However on the other hand, CAV car/ride sharing in our study includes ride-sharing which would increase number of users per car. Given the above consideration, we assume that each CAV car/ride sharing vehicle, as well as conventional one, serve 100 users.

For CAV bus, according to Department for Transport (2021c), frequent bus users (>= 3 times per week) in England in 2019 is 15% of the total population. Given that the population of England in 2019 is 56,286,961 (Office for National Statistics, 2020), and there were 32,300 buses used by local operators in England in 2019/20 (Department for Transport, 2020b), we assume each CAV bus, as well as conventional bus, serve 56,286,961*0.15/32,300 which is 261 users.

Hence, fleet size of CAV is calculated as:

$$Fleet\ size\ of\ CAV = \frac{Number\ of\ CAV\ private\ car\ users}{1.5} + \frac{Number\ of\ CAV\ car/ride\ sharing\ users}{100} + \frac{Number\ of\ CAV\ bus\ users}{261} \quad (18)$$

For non-CAV users, mode share of private car, car/ride sharing and bus is decided by the weights specified in Section 4.4.4. Number of users that each vehicle can serve is the same as the counterpart CAV mode. Fleet size of non-CAV is calculated as:

$$Fleet\ size\ of\ non\ CAV = \frac{Number\ of\ non\ CAV\ users \times 0.775}{1.5} + \frac{Number\ of\ non\ CAV\ users \times 0.056}{100} + \frac{Number\ of\ non\ CAV\ users \times 0.169}{261} \quad (19)$$

Total vehicle fleet size is this sum of fleet sizes of CAV and non-CAV. Initial total vehicle fleet size is when number of CAV users is 0, i.e., is fleet size of non-CAV with number of non-CAV users equal to total population.

4.6.1.2 Vehicle miles travelled

Vehicle miles travelled (VMT) is calculated as the ratio compared to the initial 2020 level. According to Wadud et al. (2016), VMT will increase with CAVs due to travel cost reduction and new users (e.g., the disabled, elderly and children), and the mid-value of the estimated increase is to reach 141.55% of current level. On the other hand, VMT will decrease due to new mobility services enhanced by CAVs such as ride sharing, and the mid-value of the estimated decrease is by 10%.

Considering VMT reduction by mode shift to CAV bus, according to Department for Transport (2021d, 2021e), vehicle km on local bus service in Great Britain in 2018/19 was 2316 million, while passenger km was 27.3 billion. So for bus, vehicle km per passenger km was 0.085. According to Department for Transport (2021f, 2021g), vehicle km of all road passenger vehicles in Great Britain in 2018 was 447.1 billion, while passenger km was 767 billion. So for road passenger vehicles, vehicle km per passenger km was 0.583. Given the above, we assume that if all current road passengers shift mode to CAV bus, VMT will reduce to 0.085/0.583 which is 14.58% of current level. Hence, the calculation is:

$$VMT = 1.4155 \times \frac{Number\ of\ CAV\ private\ car\ and\ car/ride\ sharing\ users}{total\ population} \times \left(1 - 0.1 \times \frac{Number\ of\ CAV\ car/ride\ sharing\ users}{Number\ of\ CAV\ private\ car\ and\ car/ride\ sharing\ users}\right) + 0.1458 \times \frac{Number\ of\ CAV\ bus\ users}{total\ population} + \frac{Number\ of\ non\ CAV\ users}{total\ population} \quad (20)$$

4.6.1.3 Network flow

Highways Agency (2002) defines the relationship between network speed and flow on urban roads in typical non-central areas as: speed(km/h) = 48.5 - 30* flow(vehicle/h/lane)/1000. Given the initial speed of 25.3 mph used in our model (see Section 4.4.1.1), we use 259 vehicles per hour per lane as initial network flow. The flow will increase as total vehicle fleet size and VMT increase. Hence the calculation is:

$$Network\ flow = 259 \times \frac{Total\ vehicle\ fleet\ size}{Initial\ total\ vehicle\ fleet\ size} \times VMT \qquad (21)$$

However, the flow is capped at 800 which is the maximum value on urban roads as specified in Highways Agency (2002).

4.6.1.4 Network speed

The speed calculation is based on the equation from Highways Agency (2002) cited in Section 4.6.1.3. On top of that, speed will increase as percentage of CAVs in total fleet increase. Results of Stanek et al. (2017) show that as percentage of CAVs increases from 0 to 100%, speed increases by 0 to 6%. We adopted this increase rate and assumed the increase is linear. Hence the calculation is:

$$Network\ speed = (48.5 - 30 \times \frac{Network\ flow}{1000}) \times (1 + 0.06 \times \frac{Fleet\ size\ of\ CAV}{Total\ vehicle\ fleet\ size}) \qquad (22)$$

4.6.1.5 Traffic accident

Traffic accident is calculated as the ratio compared to the initial 2020 level. According to US Department of Transportation (2018), more than 90% of serious vehicle crashes were attributed to human errors. We hence assume that if all vehicles are CAVs, with the most advanced CAV technology, traffic accidents will reduce by 90%. We further assume the reduction effect is linear to percentage of CAVs in total fleet, and follows a square root relationship with CAV technology advance. Finally, traffic accident will also be affected by VMT, i.e., the more vehicles travel, the more traffic accidents are likely to happen, and we assume a linear relationship between them. Hence the calculation is:

$$Traffic\ accident = \left(1 - 0.9 \times \frac{Fleet\ size\ of\ CAV}{Total\ vehicle\ fleet\ size} \times \sqrt{CAV\ technology\ advance}\right) \times VMT \qquad (23)$$

4.6.2 Energy intensity and carbon emission

CAVs can reduce transport energy intensity by e.g., automated eco-driving, platooning, right-sizing of vehicles and de-emphasised performance (Wadud et al., 2016). Wadud et al. (2016) estimated that these features together have the potential to reduce energy intensity by 7% to 79%. We use the mid value of 43% in our model, i.e., if all vehicles are CAVs, with the most advanced CAV technology, energy intensity will reduce by 43%. We calculate energy intensity as the ratio compared to the initial 2020 level. We assume the reduction effect is linear to percentage of CAVs in total fleet, and follows a square root relationship with CAV technology advance. Hence the calculation is:

$$Energy\ intensity = 1 - 0.43 \times \frac{Fleet\ size\ of\ CAV}{Total\ vehicle\ fleet\ size} \times \sqrt{CAV\ technology\ advance} \qquad (24)$$

Carbon emission is also calculated as the ratio compared to the initial 2020 level. Schipper (2002) defined four major drivers of transport carbon emissions as activity level, modal share, energy intensity and fuel carbon content. Since activity level and modal share combined can be represented by VMT (Wadud et al., 2016), and fuel carbon content is exogenous to the model and not addressed in this study, Carbon emission can be calculated by:

$$Carbon\ emission = VMT\ \times Energy\ intensity \qquad (25)$$

5 Results

5.1 CAV diffusion

5.1.1 CAV diffusion in the base, marketing, training and investment scenarios

Figure 5.1 shows the level of CAV technology advance over the simulation period of 2020-2070. In the base scenario, Technology advance increases steadily from 0.1 in 2020 to 0.76 in 2070. The marketing and the training interventions, which enhance potential users' CAV acceptance level, does not make much difference to the rate of technology development.

Increased R&D investment accelerates technology development during the first 15 years, and then the rate of development remains parallel to that in the base scenario, reaching technology advance of 0.87 in 2070. This indicates that additional R&D investment is most effective during the early stage of CAV diffusion.

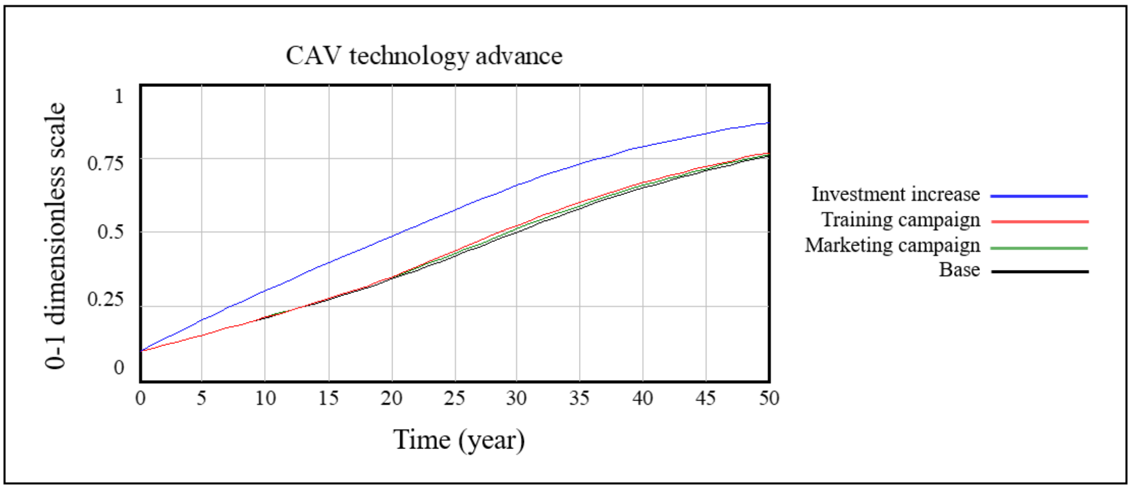

Figure 5.1: CAV technology advance in the base, marketing, training and investment scenarios.

Figure 5.2 shows numbers of CAV private car, CAV car/ride sharing and CAV bus users over the simulation period. In the base scenario, users of all modes grow slowly in the first 15 years, and then experience a rapid growth from 2035 to 2055. This is the period when the imitation effect becomes the dominant and powerful driver of user acceptance, i.e., when there are enough CAV users to influence non-users and the number of non-users is still large. The growth slows down from around 2055 as it is reaching market saturation.

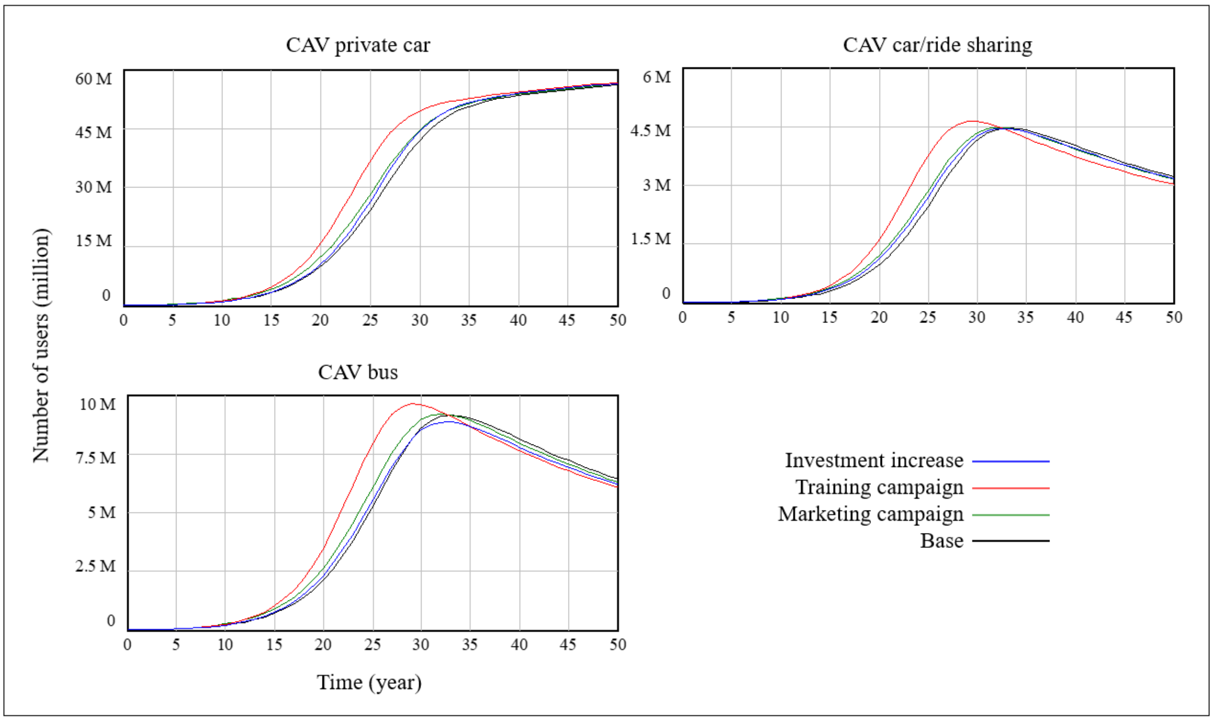

Figure 5.2: Numbers of CAV private car, CAV car/ride sharing and CAV bus users in the base, marketing, training and investment scenarios.

CAV private car is the dominant mode with 56.13 million users by 2070, accounting for 84% of the total population. Numbers of CAV car/ride sharing and CAV bus users reach their maximum of 4.45 million and 9.14 million in 2053, and then decline to 3.21 million and 6.43 million in 2070. The declines are due to the setting in the SD model that CAV car/ride sharing and CAV bus users are more likely to reconsider their choices than CAV private car users. This is further discussed in Section 5.3.2.

While marketing campaign and investment increase do not make much difference, training campaign accelerates CAV user growth from 2035. This is in line with the typical innovation diffusion pattern that the imitation effect is the main driver of diffusion, since usually only a small proportion of the population are innovators. This indicates that preparing the general public to be ready for CAV is important for CAV diffusion.

Figure 5.3 shows number of CAV users and percentage of CAV users in the total population. The growth patterns are the same as those shown in Figure 5.2. Percentage of CAV users in total population reaches the saturate level of 98% in around 2057 in the base, marketing campaign and investment increase scenarios. The level is researched earlier in 2052 in the training campaign scenario.

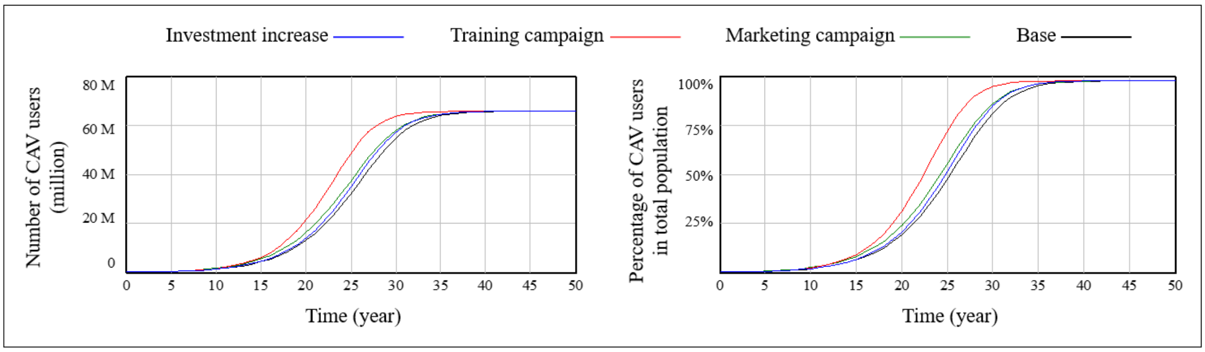

Figure 5.3: Number of CAV users and percentage of CAV users in total population in the base, marketing, training and investment scenarios.

Figure 5.4 shows fleet size of CAVs, fleet size of total vehicles and percentage of CAVs in total vehicles. Fleet size of CAVs reflects the growth pattern of CAV users, in particular, CAV private car users, since CAV car/ride sharing and CAV bus serve much more users per vehicle. In the base, marketing campaign and investment increase scenarios, fleet size of CAV reaches around 34 million after a rapid growth from 2035 to 2055 due to rapid CAV diffusion. It continues to grow at a reduced rate after 2055 and reaches 37.5 million in 2070. This is because many CAV car/ride sharing and CAV bus users switch to private cars from 2055. This is further discussed in Section 5.3.2. In the training campaign scenario, fleet size of CAV reaches 34 million earlier in 2051, but it also ends up at around 37.5 million in 2070.

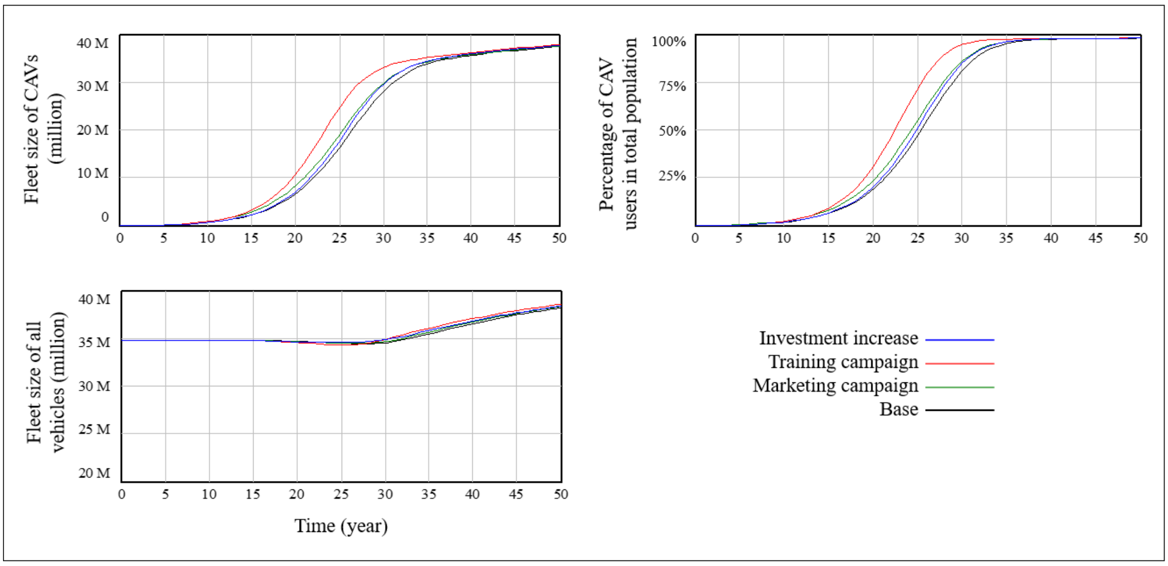

Figure 5.4: Fleet size of CAVs, fleet size of total vehicles and percentage of CAVs in total vehicles in the base, marketing, training and investment scenarios.

Fleet size of total vehicles remains largely unchanged at around 35 million in all the four scenarios till 2050. This is because mode share among new CAV users remains similar to the initial non-CAV mode share during this period, making the user-vehicle ratio largely unchanged at total fleet level. The fleet size then increases steadily to around 38 million in 2070, as many CAV car/ride sharing and CAV bus users switch to CAV private cars.

Percentage of CAVs in total vehicles mirrors the pattern of percentage of CAV users in total population, reaching the saturate level of 98% in around 2055 in all the four scenarios.

5.1.2 CAV diffusion in the base and CAV boost scenarios

Figure 5.5 shows the level of CAV technology advance in the base and CAV boost scenarios. CAV overall boost and CAV shared mobility boost do not make much difference to technology advance as compared to the base scenario, while public transport boost slightly reduces it, with technology advance reaching 0.73 in 2070, as compared to 0.76 in the base scenario. This is due to lower R&D investment from CAV public transport market.

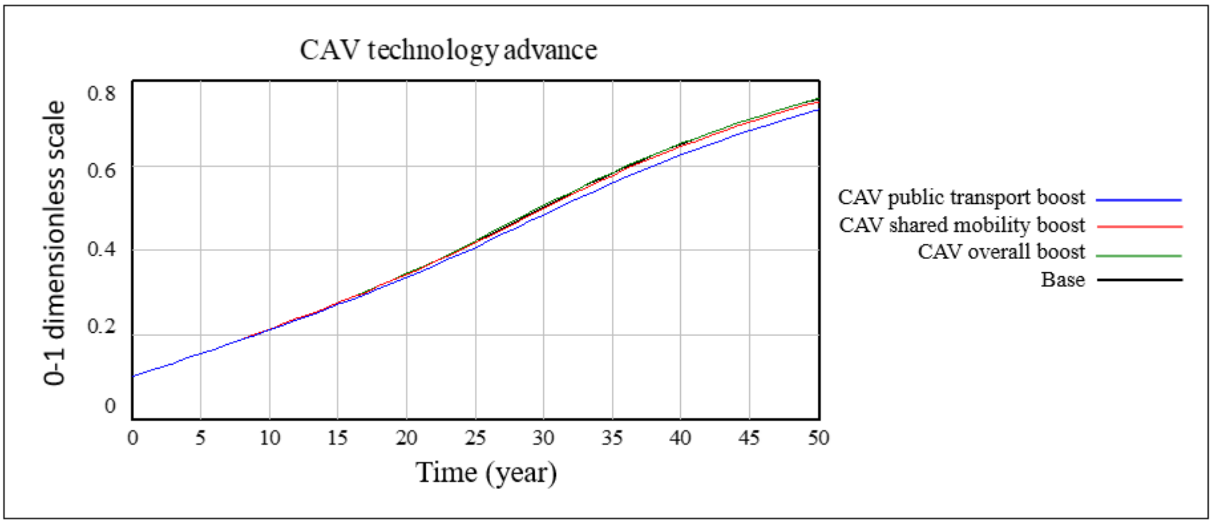

Figure 5.5: Level of CAV technology advance in the base and CAV boost scenarios.

Figure 5.6 shows numbers of CAV private car, CAV car/ride sharing and CAV bus users in the base and CAV boost scenarios. The overall boost does not show a clear impact on user choice, since utilities of all the three modes are improved in a balanced manner and hence probability of choosing among them are not very much affected. CAV shared mobility boost, with which utilities of CAV car/ride sharing and CAV bus are improved while CAV private car is unaffected, sees CAV private car users reduce to 49.67 million in 2070 as compared to 56.13 million in the base scenario, and CAV car/ride sharing and CAV bus users increase to 5.89 million and 9.96 million in 2070 as compared to 3.21 million and 6.43 million respectively in the base scenario. CAV public transport boost, with which utilities of CAV private car is reduced and CAV bus is further improved, sees CAV private car users reduce to 40.49 million in 2070, CAV car/ride sharing users increase slightly to 4.22 million in 2070, while CAV bus users experience a large increase to 20.21 million in 2070.

The growth patterns however remain the same as those in the base scenario, i.e., while number of CAV private car users continues to grow after 2053 although at a reduced rate, numbers of CAV car/ride sharing and CAV bus users reach their maximum in 2053 and then start to decline.

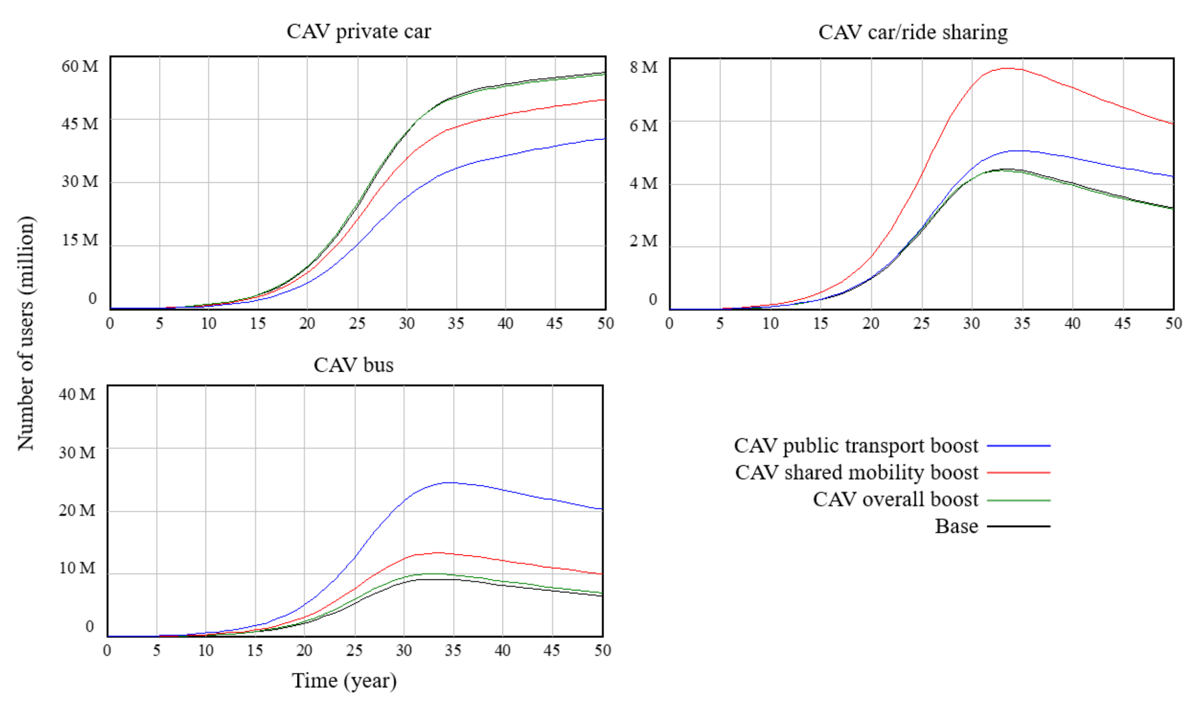

Figure 5.6: Numbers of CAV private car, CAV car/ride sharing and CAV bus users in the base and CAV boost scenarios.

Figure 5.7 shows number of CAV users and percentage of CAV users in total population in the base and CAV boost scenarios. The growth patterns in the CAV boost scenarios are all the same as that in the base scenario, with percentage of CAV users in total population reaching the saturate level of 98% in around 2057.

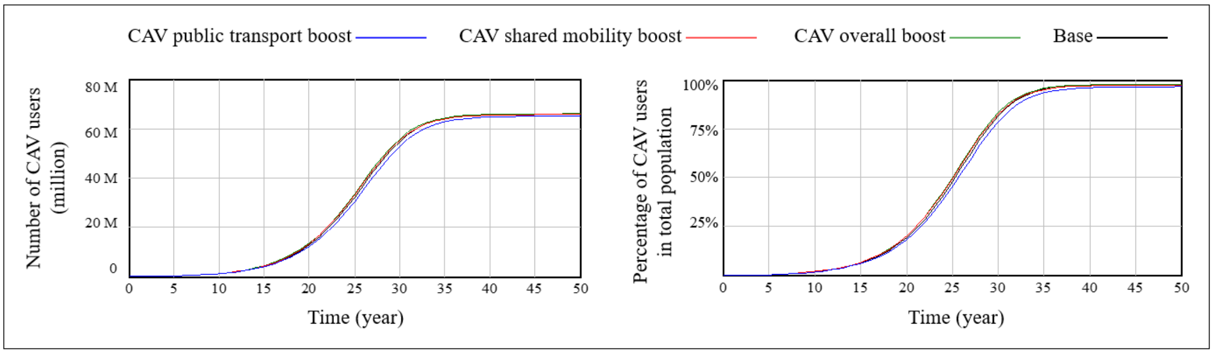

Figure 5.7: Number of CAV users and percentage of CAV users in total population in the base and CAV boost scenarios.

Figure 5.8 shows fleet size of CAVs, fleet size of total vehicles and percentage of CAVs in total vehicles in the base and CAV boost scenarios. Fleet size of CAVs reflects the growth pattern of CAV users, in particular, CAV private car users. Fleet size of CAVs in the CAV overall boost scenario is similar to that in the base scenario, reaching 33.55 million after a rapid growth from 2035 to 2055 due to rapid CAV diffusion, and then continuing to grow to 37.16 million in 2070. Fleet size of CAVs is smaller in the CAV shared mobility boost and CAV public transport boost scenarios, reaching 28.93 million and 22.38 million in 2055, and 33.21 million and 27.11 million in 2070 respectively.

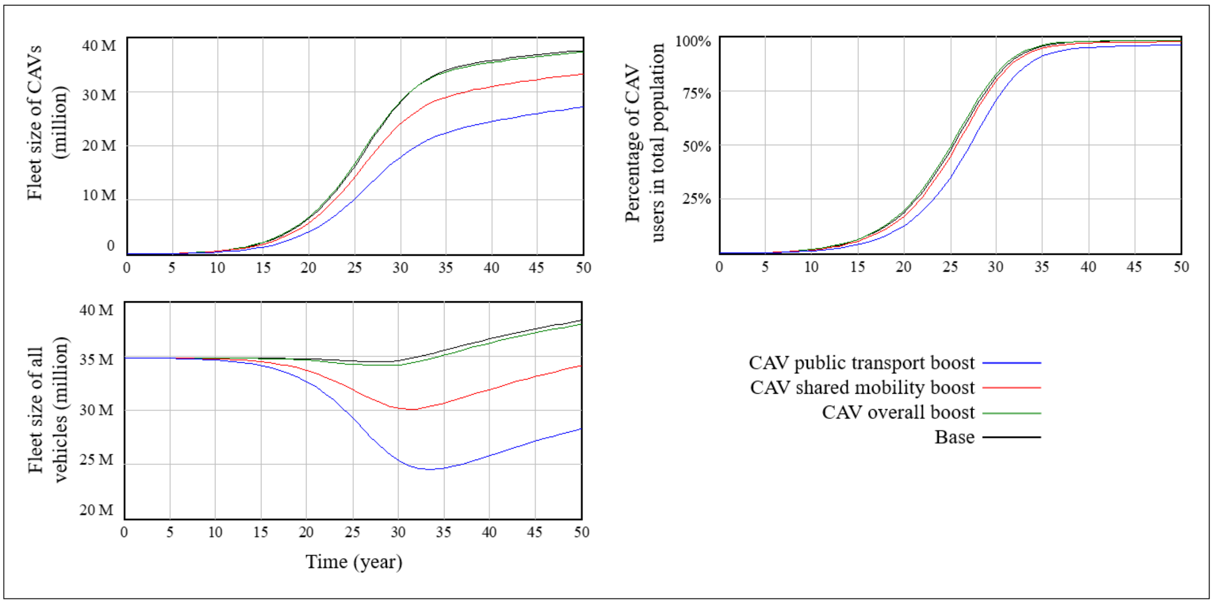

Figure 5.8: Fleet size of CAVs, fleet size of total vehicles and percentage of CAVs in total vehicles in the base and CAV boost scenarios.

Fleet size of total vehicles in the CAV overall boost scenario is again similar to that in the base scenario, slightly reducing from 34.81 million in 2020 to 34.05 million in 2048 and then increasing to 37.89 million in 2070.

With reduced car ownership, fleet size of total vehicles in the CAV shared mobility boost scenario drops to 30.08 million in 2051 and then rises to 34.09 million in 2070, which is still lower than the initial size of 34.81 million in 2020. In the CAV public transport boost scenario, it drops to the lowest of 24.53 million in 2053 and then rises to 28.30 million in 2070, which is still much lower than the initial size in 2020.

Similar to the base scenario, percentage of CAVs in total vehicles in the CAV overall boost and CAV shared mobility boost scenarios mirrors the pattern of percentage of CAV users in total population, reaching the saturate level of 98% in around 2055. The percentage is slightly lower in the CAV public transport boost scenario, reaching the saturate level of 96% in around 2060.

5.2 CAV impacts

5.2.1 CAV impacts in the base, marketing, training and investment scenarios

Figure 5.9 show average travel time and average travel cost in the base, marketing, training and investment scenarios. They are average travel time and cost of CAV private car, CAV car/ride sharing, CAV bus and the non-CAV option weighted by numbers of their users.

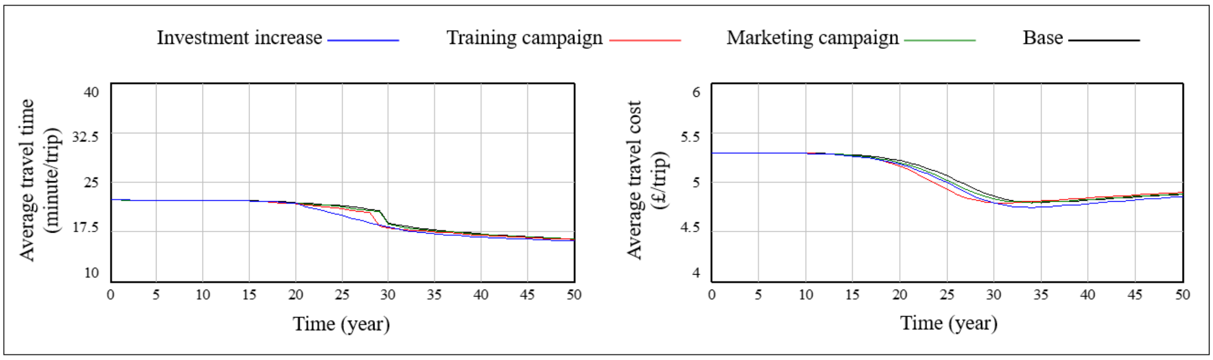

Figure 5.9: Average travel time and average travel cost in the base, marketing, training and investment scenarios.

Average travel time remains largely constantly at around 22.3 minutes in the first 20 years in all the four scenarios. It starts to reduce from 2040, with a rapid drop from around 20.5 minutes to 18.5 minutes over 2049 to 2050 in the base, marketing and training scenarios. This is caused by the availability of self-parking function of CAVs which reduces CAV private car parking time. The reduction is smoother in the investment scenario where the self-parking function was achieved earlier when number of CAV private car users is not yet dominant, and hence the sudden parking time reduction only gradually becomes obvious over the 10 years from 2020 to 2030 during which number of CAV private car users enjoys a rapid growth. By 2070, average travel time drops to around 16.5 minutes in all the four scenarios.

Average travel cost is similar across the four scenarios. It remains constant at around £5.30 during the first 15 years, and then drops to £4.8 in around 2033. The drop over this period is due to the continuous reductions of travel costs of CAV private car, CAV car/ride sharing and CAV bus, and the rapid growths of their users. After that, average travel cost grows slowly to around £4.90 in 2070 in all the four scenarios. The growth is due to many CAV car/ride sharing and CAV bus users shifting to CAV private cars of which the travel cost is higher.

Figure 5.10 shows impact of CAV on mode share, i.e., percentages of private car users and bus users in total population in the base, marketing, training and investment scenarios. Private car users include CAV private car users and the share of private car users among non-CAV users, and the same for bus users.

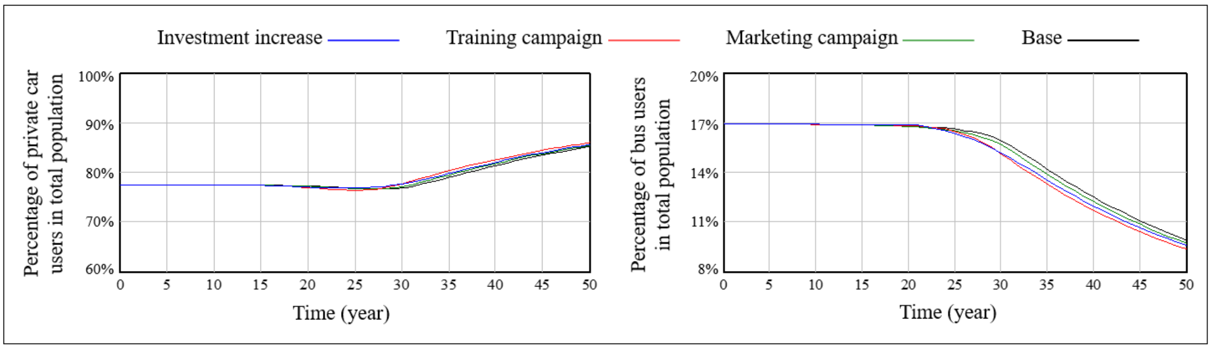

Figure 5.10: Percentages of private car users and bus users in total population in the base, marketing, training and investment scenarios.

In all the four scenarios, percentage of private car users remains largely constant at around 77% from 2020 to 2050. It then starts to grow steadily and reaches around 86% in 2070. Percentage of bus users, on the other hand, remains largely constant at around 17% from 2020 to 2045 in all the four scenarios, and then gradually drops to around 10% in 2070. So, without intervention, CAVs are likely to lead to higher mode share of private cars.

Figure 5.11 shows VMT, energy intensity, carbon emission and traffic accident in the base, marketing, training and investment scenarios. They are all ratios compared to the initial levels in 2020.

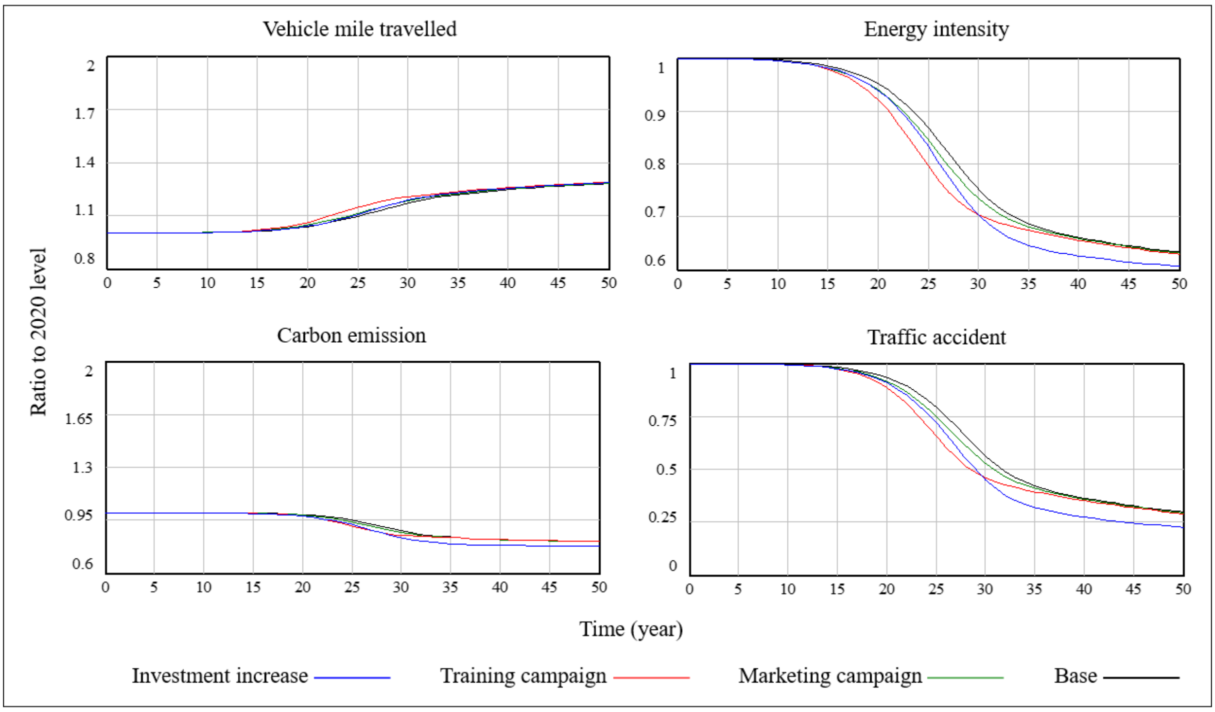

Figure 5.11: Vehicle mile travelled, energy intensity, carbon emission and traffic accident in the base, marketing, training and investment scenarios.

VMT is largely the same across the four scenarios. It remains constant at around 1 from 2020 to 2035, and then experiences relatively rapid growth and reaches around 1.21 in 2053, i.e., 21% increase. This is due to rapid diffusion of CAVs during this period, in particular CAV private cars which increase VMT. The growth in the training scenario is slightly more rapid than other scenarios due to accelerated CAV diffusion. VMT then continues to grow at a reduced rate to around 1.29 in 2070 in all the four scenarios.

Energy intensity reduces in an inverse S-shape pattern, following the S-shaped CAV diffusion (i.e., percentage of CAVs in total fleet). In the base scenario, it drops to 0.63 in 2070, i.e., 37% reduction. Both marketing campaign and training campaign accelerate the reduction, especially the latter. The reduction acceleration effect of R&D investment increase lies between marketing campaign and training campaign. But in addition to accelerating reduction rate, it also enhances the reduction extent to 39%.

With the large reduction in energy intensity, carbon emission decreases over the simulation period despite increase in VMT. The reduction mainly occurs during the 15 years from 2040 to 2055, and by 2070, carbon emission reduces to 0.81 in the base, marketing and training scenarios, and to 0.78 in the investment scenario.

Traffic accident also reduces in an inverse S-shape pattern, following the S-shaped CAV diffusion, and the effects of marketing campaign, training campaign and R&D investment increase are similar to those on energy intensity. Traffic accident reduces to 0.30 in the base, marketing and training scenarios, and to 0.23 in the investment scenario.

5.2.2 CAV impacts in the base and CAV boost scenarios

Figure 5.12 show average travel time and average travel cost in the base and CAV boost scenarios. Average travel time remains largely constant at around 22.3 minutes in the first 15 years and then starts to reduce in all the four scenarios. The reduction varies across scenarios, and it reduces to 16.5, 14.8, 15.7 and 17.6 minutes in 2070 in the base, CAV overall boost, CAV shared mobility boost and CAV public transport boost scenarios respectively. The average travel times in all the four scenarios experience a sudden drop around 2050 which is caused by the availability of self-parking function of CAVs which reduces CAV private car parking time.

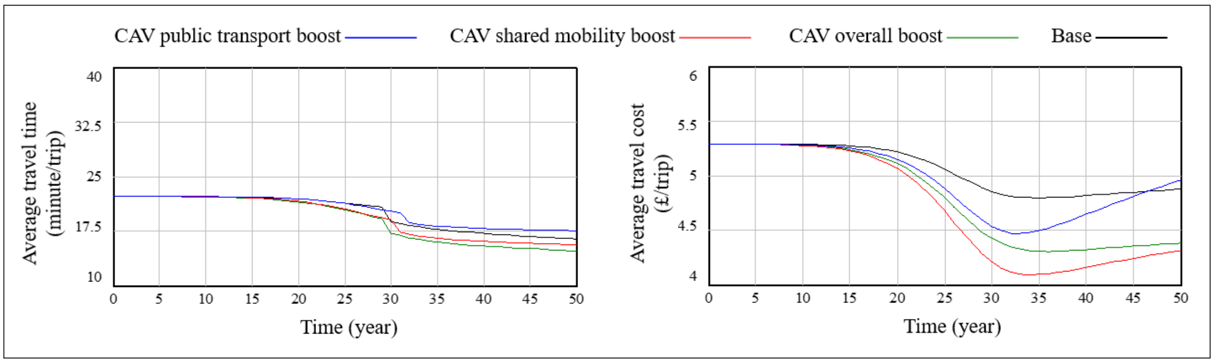

Figure 5.12: Average travel time and average travel cost in the base and CAV boost scenarios.

Average travel cost reduces in all the four scenarios, but the reductions vary a lot across scenarios. The CAV shared mobility boost scenario, in which travel costs of CAV car/ride sharing and CAV bus are reduced which also increases their numbers of users, see the largest reduction. It reaches the lowest cost of £4.10 in 2054, £0.70 lower than the lowest in the base scenario. In the CAV overall boost and CAV public transport boost scenarios, the lowest cost is £4.30 in 2056 and £4.50 in 2053 respectively.

Due to CAV car/ride sharing and CAV bus users switching to CAV private cars, average travel costs increase from around 2053 in all the four scenarios, researching £4.90, £4.40, £4.30 and £5.00 in the base, CAV overall boost, CAV shared mobility boost and CAV public transport boost scenarios respectively. Noticeably, cost becomes higher in the CAV public transport boost scenario than in the base scenario. This is due to increase travel cost of CAV private car and the still large number of CAV private car users in the CAV public transport boost scenario.

Figure 5.13 shows percentages of private car users and bus users in total population in the base and CAV boost scenarios. While CAV overall boost does not make mode share much different from the base scenario, CAV shared mobility boost and CAV public transport boost reduce share of private car from 78% to 67% and 54% respectively in 2053. Due to users switching to CAV private cars during the later stage of simulation period, they increase to 76% and 63% respectively in 2070, still much lower than the 85% in the base scenario and 84% in the CAV overall boost scenario in the same year.

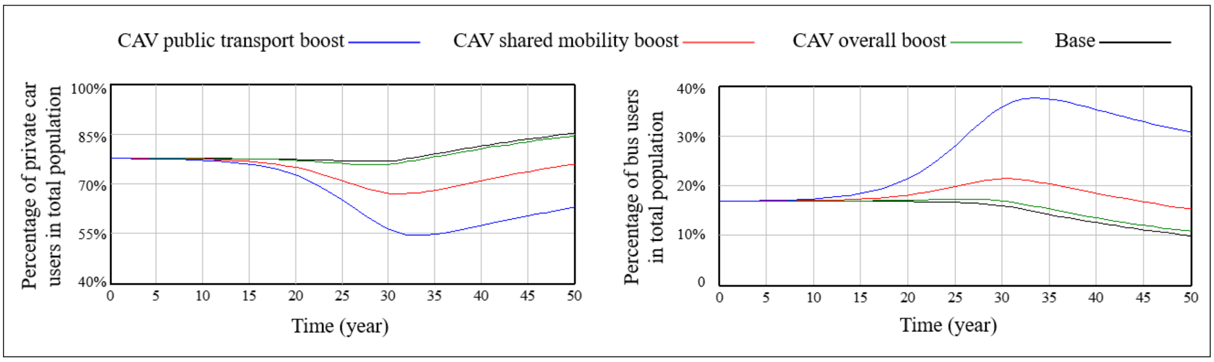

Figure 5.13: Percentages of private car users and bus users in total population in the base and CAV boost scenarios.

Changes in share of bus reflect changes in share of private car, with share of bus increases from 17% to the highest of 38% in 2053 in the CAV public transport boost scenario. Increase in the CAV shared mobility boost scenario is small, only reaching 21% in 2051. This is because of a larger increase in share of car/ride sharing. The shares in 2070 are 10%, 11%, 15% and 31% in the base, CAV overall boost, CAV shared mobility boost and CAV public transport boost scenarios respectively.

Figure 5.14 shows VMT, energy intensity, carbon emission and traffic accident in the base and CAV boost scenarios. They are all ratios compared to the initial levels in 2020.

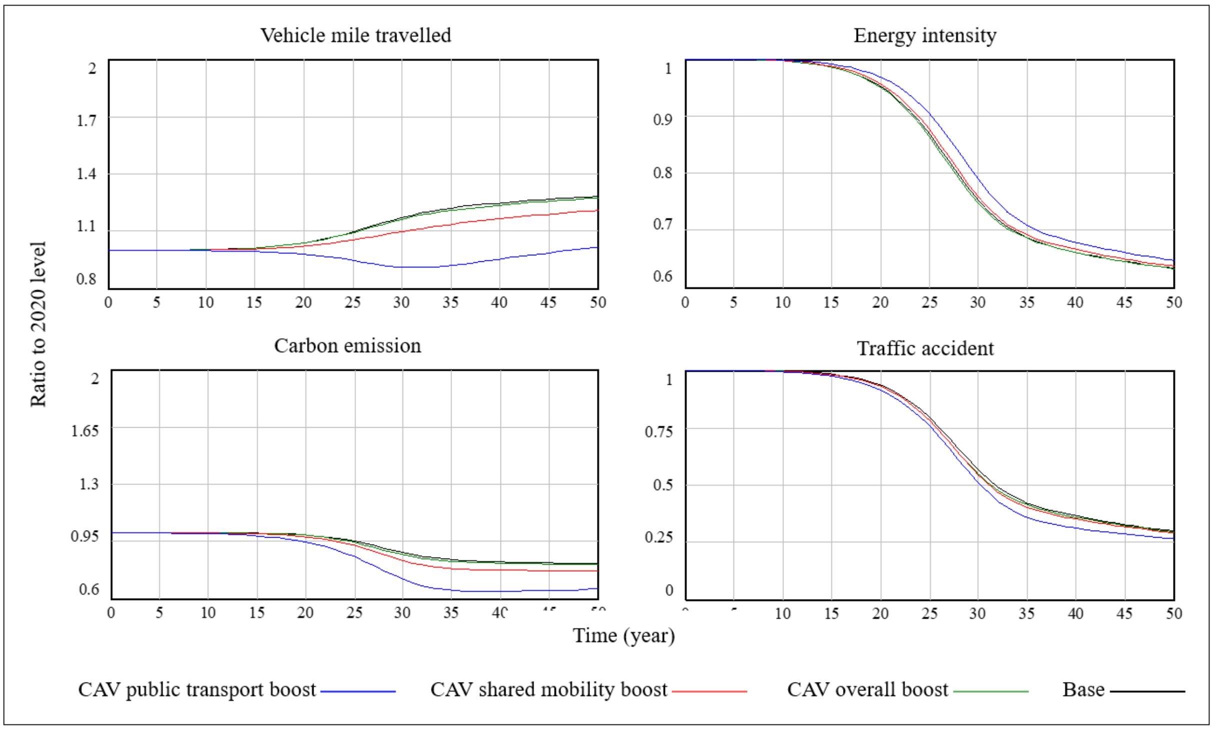

Figure 5.14: Vehicle mile travelled, energy intensity, carbon emission and traffic accident in the base and CAV boost scenarios.

Changes in VMT vary across the four scenarios, and reflects changes in mode share. VMT in the CAV overall boost scenario is largely the same as that in the base scenario, starting to increase from around 2035 and reaching 1.27 in 2070, i.e., 27% increase. Increase in the CAV shared mobility boost scenario is smaller, reaching 1.21 in 2070. With more people using bus, VMT decreases in the CAV public transport boost scenario. It reaches the lowest level of 0.91 in 2052 and then increases to 1.01 in 2070.

Energy intensity reduces in an inverse S-shape pattern, following the S-shaped CAV diffusion. Energy intensity in the CAV overall boost and CAV shared mobility boost scenarios are largely the same as that in the base scenario, dropping to 0.63 in 2070, i.e., 37% reduction. The reduction is slightly smaller in the CAV public transport boost scenario, dropping to 0.65 in 2070, due to slower CAV technology development.

Carbon emission decreases in all the four scenarios, with the largest decrease seen in the CAV public transport boost scenario, which has by far the lowest VMT. Carbon emission remains largely constant from 2020 to 2035, and then reduces to 0.81, 0.81, 0.77 and 0.66 in the base, CAV overall boost, CAV shared mobility boost and CAV public transport boost scenario respectively, with reductions all mainly occur during the 15 years from 2040 to 2055.

Traffic accident also reduces in an inverse S-shape pattern, following the S-shaped CAV diffusion. It reduces to around 0.30 in the base, CAV overall boost and CAV shared mobility boost scenarios, and to 0.27 in the CAV public transport boost scenario due to lower VMT.

5.3 Sensitivity tests

5.3.1 Overall test results

Many of the results in Sections 5.1 and 5.2 are sensitive to the values of constants used in this SD model. Since many of the model constant values were based on literature and assumptions, and there is currently little CAV use data available for calibration, the SD model was subjected to sensitivity tests. To do the tests, each of all model constant was varied univariately by ±20%, which is a commonly applied range for sensitivity test (Sterman, 2000), and changes in some key output variables were recorded. The key output variables used were *Number of CAV private car users, Number of CAV car/ride sharing users, Number of CAV bus users* and *Carbon emission*. These sensitivity tests were conducted in the context of the base scenario.

Table 5.1 shows sensitive results where the ±20% change in a constant causes noticeable changes in any of the four key output variables. Numbers of CAV users of all modes are sensitive to *coefficient q*, which determines the yearly rate of potential CAV users to be influenced by CAV users and become willing to consider CAVs, i.e., how likely a person would be willing to try CAVs after seeing other people using them. This further highlights the importance of improving public acceptance of and readiness for CAVs in accelerating CAV diffusion.

Numbers of CAV car/ride sharing users and CAV bus users are sensitive to some constants that affect travel time and travel cost of different options. Number of CAV car/ride sharing users is particularly sensitive due to its relatively small user number. This raises concerns on the robustness of the modelling results on mode share, given current uncertainties in CAV costs and travel time impacts. Nevertheless, number of CAV private car users, which accounts for the majority of the total population, is not sensitive to these constant, hence modelling results on overall CAV diffusion is more robust. The sensitivities of numbers of CAV car/ride sharing users and CAV bus users also indicate the potential of policy interventions on travel time and travel cost to promote more sustainable mode share.

Table 5.1: Results of sensitivity tests where changes in input constants cause noticable changes in key output variables

	Sensitivity test input constant base values	**Changes in key output variables**			
		Number of CAV private car users	**Number of CAV car/ride sharing users**	**Number of CAV bus users**	**Carbon emission**
Coefficient q	0.341865	-27% - 15%	-26% - 10%	-26% - 11%	
Cost reduction extent of car/ride sharing due to tech advance	60%		-10% - 11%		
Energy intensity reduction extent	43%				-12% - 12%
Initial CAV bus in vehicle time	29 minutes			-20% - 24%	
Initial CAV car/ride sharing travel time	16.86 minutes		-11% - 12%		
Initial CAV car/ride sharing usage cost	£8.536		-19% - 24%		
Initial CAV private car in vehicle time	11.86 minutes		-8% - 9%	-9% - 9%	
Initial CAV private car usage cost	£5.2		-16% - 18%	-16% – 19%	
Percentage of CAV car/ride sharing users reconsider choice every year	5%		-15% - 19%		
Percentage of CAV bus users reconsider choice every year	5%			-15% - 18%	
VMT change due to travel cost reduction and new users	142%				-20% - 20%

Numbers of CAV car/ride sharing users and CAV bus users are also sensitive to percentage of users reconsidering choice every year. This is discussed in more detail in Section 5.3.2.

Carbon emission is sensitive to *energy intensity reduction extent*, which determines the maximum energy intensity reduction potential if all vehicles are CAVs with the most advanced CAV technology, and to *VMT change due to travel cost reduction and new users*. Again, there are still uncertainties on these constants, so the modelling results on carbon emission need to be used with caution.

5.3.2 Sensitivity to user reconsideration

In this SD model, we assume that every year, 1% of CAV private car users and 5% of CAV car/ride sharing and CAV bus users will reconsider their choice, since it is common that every now and then people will change their travel mode.

As is shown in Section 5.1, this leads to declines in number of CAV car/ride sharing users and CAV bus users in the later stage of the simulated period. This is because as the cumulative numbers of their users increases, the numbers of their users reconsidering choice also increase, and only a small proportion of them will return to these two modes since the utility of CAV private car is constantly higher.

On the other hand, number of potential new users is decreasing. So from a certain time point, cumulative numbers of CAV car/ride sharing users and CAV bus users start to decrease. With an extended simulation period of 200 years (2020-2220), it shows that an equilibrium will be reached around 2170 in the base scenario, with numbers of CAV private car users, CAV car/ride sharing users and CAV bus users being 61.66 million, 1.56 million and 2.86 million respectively (Figure 5.15).

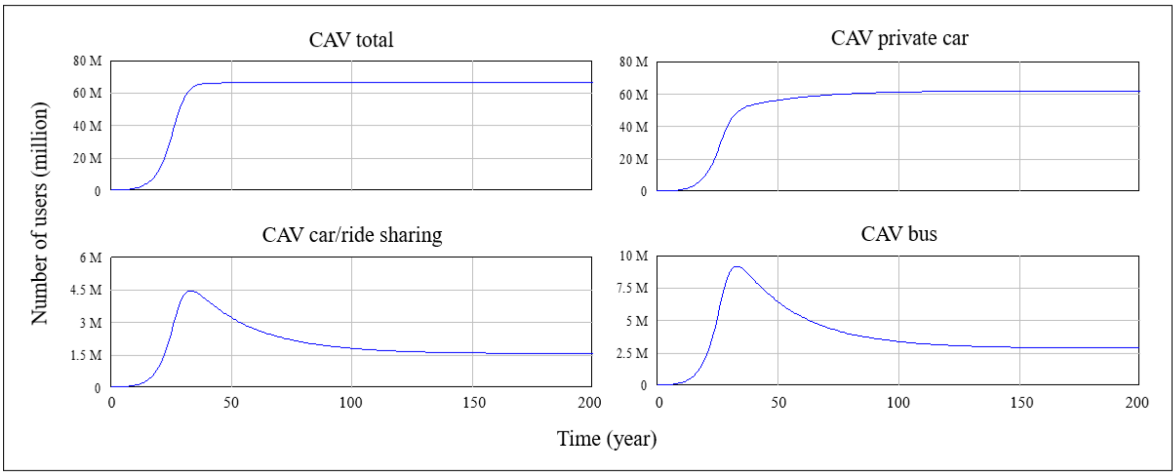

Figure 5.15: Numbers of CAV private car, CAV car/ride sharing and CAV bus users in the base scenario over an extended simulation period.

To further understand the impacts of this reconsideration setting, we tested four more different settings: a. 1% for CAV private car, 2% for CAV car/ride sharing and CAV bus; b. all 5%; c. all 1%; d. all 0%. Results are shown in Figure 5.16. it shows that with a reduced reconsideration rate of 2%, declines of numbers of CAV car/ride sharing and CAV bus users slowed down a lot. With equal reconsideration rate with CAV private car users, the declines are avoided. The implication is that, to achieve sustainable mode share more effectively, apart from enhancing utilities of sustainable modes, it is also important to build loyalty of their users (e.g., by introducing customer loyalty programmes), and/or to provide incentives to encourage car owners to give more considerations to other modes.

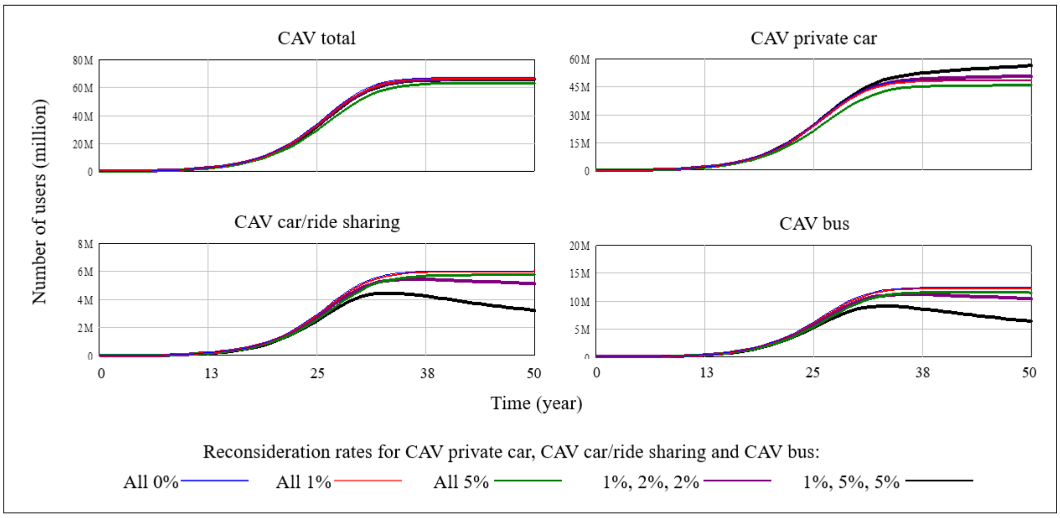

Figure 5.16: Numbers of CAV private car, CAV car/ride sharing and CAV bus users in the base scenario with different reconsideration settings.

6 Policy recommendations

In this section, we summarise the simulation results and propose policy recommendations for accelerating CAV diffusion and optimising CAV impacts.

6.1 Summary of simulation results

6.1.1 Results of CAV diffusion

The simulation results suggest that without interventions, i.e., in the base scenario, number of CAV users will start to increase rapidly from around 2035, and reaches a saturation level of 98% of the total population of 67.22 million in the UK in around 2057. Among these CAV users, more than 80% are CAV private car users. Fleet size of CAVs reaches 37.5 million in 2070, which is also 98% of total vehicles.

Enhancing user acceptance by training campaign, which prepares the majority of the population to be ready for CAVs and encourages their decisions to imitate the emerging norms, accelerate CAV diffusion, and the market saturation of 98% is researched earlier in 2052.

Enhancing user acceptance by marketing campaign, which enhances early adopters’ desire to innovate regardless of the rest of the society, does not make much difference to the diffusion process, nor does R&D investment increase, which accelerates CAV technology development but does not make fundamental changes to CAV utilities in our model.

The three CAV boost interventions do not make much difference to user penetration. The do change the shares of the three CAV modes and hence fleet size of CAVs and fleet penetration. In particular, with CAV public transport boost, fleet size of CAVs reaches only 27.1 million, accounting for 96% of total vehicles.

6.1.2 Results of CAV impacts

The simulation results suggest that without interventions, i.e., in the base scenario, CAV technology advance and CAV diffusion lead to reductions in average travel time and average travel cost, from 22.3 minutes and £5.3 per trip in 2020 to 16.5 minutes and £4.9 per trip in 2070. Share of private car users increases from 77% in 2020 to 86% in 2070, while share of bus users decreases from 17% to 10%. Despite a 29% increase in VMT, carbon emission decreases by 19%, due to a large decrease of 37% in energy intensity. Traffic accidents also see a large decrease of 70%.

Interventions that enhance user acceptance rate do not make much difference to these CAV impacts, except R&D investment increase which further reduces energy intensity and traffic accidents by small percentages.

The three CAV boost interventions have much stronger effects. With supportive interventions that reduce travel time and travel cost of CAV car/ride sharing and CAV bus, mode share shifts noticeably from private car to bus, with share of bus users reaching the highest of 38% in 2053 in the CAV public transport boost scenario. However, due to constant mode changes of all users and the lower likelihood for car owners to change mode, share of bus users starts to decrease after the peak level.

Higher shares of car/ride sharing and bus also reduce VMT and carbon emission. In particular, in the CAV public transport boost scenario, VMT reduces by up to 9% in 2052 and carbon emission reduces by 34% in 2070.

6.2 Policy recommendations for accelerating CAV diffusion

As CAV technology develops, utility of CAV will be larger than that of conventional vehicles. However, this does not guarantee successful diffusion of CAVs. CAVs first need to be accepted by potential users before they will be considered in the potential users’ choice making, and eventually be adopted. Well-designed interventions can help enhance user acceptance and hence accelerate CAV diffusion.

CAV diffusion will be very slow in the beginning, partly because CAV technology is not mature enough and hence utility of CAVs is not particularly high, but more importantly, most people would be reluctant to accept radical innovations and changes. Marketing activities especially advertising that encourages people’s desire to innovate, e.g., by inspiring their technological motivation and/or responds to their environmental concern, would be most effective in the early stage of innovation diffusion to encourage the innovators and early adopters to accept and adopt CAVs. These people as CAV users can then influence the rest majority of the population. However, effects of such interventions on overall CAV diffusion are not very strong.

The adoption by the rest majority of the population through imitation effect, i.e., following existing CAV users and the emerging social norms, would be the main driver of CAV diffusion. To stimulate this imitation effect and accelerate CAV diffusion, it would be very helpful to provide training programmes and organise education campaigns to develop people’s trust and familiarity to CAVs, as well as relevant infrastructure, services, rules and regulations, so they can feel confident and comfortable to try CAVs when they need to imitate the others. Marketing activities that enforce social norms, e.g., regular presentations of CAVs in films, TV programmes, influencers’ social media, etc., can also help stimulate imitation effect.

Increasing R&D investment can accelerate CAV technology development, which can also enhance user acceptance by improving CAVs’ attributes and utility. However, knowledge transfer from R&D investment to technology development takes time, the enhancing effect on user acceptance will not be obvious until a later stage in the diffusion process, while user acceptance is more critical in the early-mid stage. Hence, attempts to enhance user acceptance through R&D investment is unlikely to be as cost effective as training and marketing. Nevertheless, R&D investment has other benefits (see Section 6.3).

Promoting shared CAVs and CAV public transport will reduce fleet size of CAVs, which from certain perspectives discourages CAV diffusion. However, this is unlikely to reduce or delay CAV market penetration very much in terms of percentage of CAV users in total population and percentage of CAVs in total fleet. On the other hand, promoting shared CAVs and CAV public transport can help optimise CAV impacts as to be mentioned in Section 6.3.

6.3 Policy recommendations for optimising CAV impacts

Diffusion of CAVs is expected to bring many benefits, e.g., improving energy efficiency by mitigating road congestions and implementing eco-driving, making roads safter by avoiding human-driver errors and deficiencies, reducing travel time by making road network more efficient and better travel planning, providing mobility services that are more affordable by reducing costs of human drivers, and more accessible by serving users who are unwilling or unable to drive. However, CAVs may also increase car dependence and encourage more car trips and longer commutes, leading to higher VMT which could consequently means more pollutions and carbon emission, and cities sprawling into suburbs which is not sustainable development. There are also risks that CAVs may increase mobility disparity between the socially advantaged and disadvantaged, due to potentially higher travel costs of CAV cars and reduced provision of public transport as a consequence of competition from CAV cars. Some interventions can be used to help achieve more positive impacts of CAVs and minimise the negative impacts.

Technology development is certainly critical for achieving all these positive impacts. In particular, results of the SD model show that without sufficient R&D investment, CAVs may not be able to reach their full potential in energy intensity and traffic accident reductions, despite an almost full market penetration.

However, how we use CAVs is also important. Results of the SD model suggest that encouraging more people to use shared CAVs and CAV public transport contributes to more sustainable mobility. With large enough user groups, shared CAVs also have the advantage of lowering travel cost without compromising travel time too much.

To encourage people to use shared CAVs and CAV public transport, subsidies can be provided for CAV public transport services with priority use of road space where demand for public transport is high, to make it more attractive with more frequent services, even lower travel cost and shortened travel time, and shared CAV services be designed to serve first/last-mile connections to the public transport to make it more accessible, more efficient and more convenient. Where demand for public transport is low, e.g., in remote low-density areas, shared CAV services can be designed to provide efficient shared mobility that is on-demand and door-to-door. Current car designs that are mainly for private ownership or use may not fit these services very well and may need to be redesigned.

On the other hand, interventions can also be made to discourage excessive use of private CAVs, e.g. increasing their travel time and travel cost by implementing restrictions on road use, higher road toll and/or higher tax. The additional revenue from higher road toll and tax can be used to fund CAV technology development, infrastructure and services of shared CAVs and CAV public transport.

7 Conclusions

This deliverable aims to simulate the diffusion of CAVs using a system dynamics based model and based on the Bass innovation diffusion theory, to explore how users perception, CAV technological advance and CAV utilities affect user acceptance and CAV diffusion, the wider mobility and society impacts of CAV diffusion, and how these in return influence users perception, CAV technological advance and CAV utilities. A list of indicators for CAV diffusion and CAV impacts were tested in six scenarios in addition to the base scenario, to assess the long-term impacts of possible interventions that are designed to stimulate CAV diffusion and to optimise CAV impacts.

The simulation results suggest that without interventions CAV diffusion will be slow before 2035, and then increase rapidly and reach market saturation of 98% in around 2057. CAV diffusion will lead to reductions in average travel time, average travel cost, carbon emission and traffic accident.

Training campaign that prepares the majority of the population to be ready for CAVs is more effective than marketing campaign in accelerating CAV diffusion. Promoting shared CAVs and CAV public transport can contribute to more sustainable and more affordable mobility with CAVs, although this may lead to smaller CAV market size in terms of CAV sale.

The model however has some limitations. Not all potential CAV impacts and feedback loops are considered, e.g., impact on labour market and their feedback to public acceptance. Also, the model focuses on passenger transport so does not include CAV diffusion in freight transport. Adding these factors into the model may change the simulation results in different directions. Hence, the absolute forecasts should not be seen as the primary outputs of the simulation, rather, it is the comparative analysis of the modelled factors of interest that is most useful. Moreover, like most other SD models, if not all, this SD model is based on many assumptions as described in Section 4, due to lack of existing CAV market data and uncertainties in CAV technology and policy development. Hence, results need to be interpreted and used with caution. Nevertheless, sensitivity tests show that key model behaviours are robust and results are reliable for qualitative policy implications. As more and more CAV data become available, the model can be further calibrated and optimised to improve simulation accuracy.

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9 Appendix: Model constants, equations for variables and levels

Model constants

Table 9.1 - Model constants

Constant	Unit	Value	Description	Source
% CAV CS users reconsider choice	%/year	0.05	Percentage of CAV car/ride sharing users reconsidering choice every year	Assumption
% CAV PC users reconsider choice	%/year	0.01	Percentage of CAV private car users reconsidering choice every year	Assumption
% CAV PT users reconsider choice	%/year	0.05	Percentage of CAV bus users reconsidering choice every year	Assumption
Accident reduction	dmnl	0.9	The extent of traffic accident reduction is up to 90%, when all vehicles are CAVs and with the most advanced CAV technology.	US Department of Transportation (2018); Assumption
Accident reduction power tech advance	dmnl	0.5	A square root relationship of traffic accident reduction by CAV technology advance, i.e., CAV technology advance raised to the power of 0.5.	Assumption
ASC CS	dmnl	-2.11	Alternative specific constant for CAV car/ride sharing in the utility function, representing unobserved preference.	Calibrated the initial choice probabilities to current mode share in England

ASC non CAV	dmnl	-0.31	Alternative specific constant for the non CAV option in the utility function, representing unobserved preference.	Average of the 3 CAV options
ASC PC	dmnl	0	Alternative specific constant for CAV private car in the utility function, representing unobserved preference.	Reference option
ASC PT	dmnl	-1.12	Alternative specific constant for CAV bus in the utility function, representing unobserved preference.	Calibrated the initial choice probabilities to current mode share in England
β_{tc}	dmnl	-0.2	Travel cost coefficient in utility function.	Hensher & Rose (2007); Assumption
β_{tt}	dmnl	-0.04	Travel time coefficient in utility function.	Hensher & Rose (2007); Assumption
Coefficient p	dmnl	0.001	Coefficient p of innovation effect in the Bass model	Lavasani et al. (2016)
Coefficient q	dmnl	0.341865	Coefficient q of imitation effect in the Bass model	Lavasani et al. (2016)
Cost reduction extent CS tech advance	dmnl	0.6	The extent of CAV car/ride sharing travel cost reduction by CAV technology advance is up to 60%.	Bösch et al. (2018); NimbleFins (2021); Assumption
Cost reduction extent CS user number	dmnl	0.25	The extent of CAV car/ride sharing travel cost reduction by user number increase is up to 25%.	Assumption

Cost reduction power CS user number	dmnl	0.5	A square root relationship of CAV car/ride sharing travel cost reduction by user number increase, i.e., percentage of CAV car/ride sharing users in total population raised to the power of 0.5.	Assumption
Cost reduction power PT user number	dmnl	0.5	A square root relationship of CAV bus travel cost reduction by user number increase, i.e., percentage of CAV bus users in total population raised to the power of 0.5.	Assumption
Cost reduction extent PC usage tech advance	dmnl	0.2	The extent of CAV private car usage cost reduction by CAV technology advance is up to 20%.	Bösch et al. (2018); NimbleFins (2021); Assumption
Cost reduction extent PT tech advance	dmnl	0.4	The extent of CAV bus travel cost reduction by CAV technology advance is up to 40%.	Assumption
Cost reduction extent PT user number	dmnl	0.25	The extent of CAV bus travel cost reduction by user number increase is up to 25%.	Assumption
Energy intensity reduction	dmnl	0.43	The extent of energy intensity reduction is up to 43%, when all vehicles are CAVs and with the most advanced CAV technology	Wadud et al. (2016); Assumption
Energy intensity reduction power tech advance	dmnl	0.5	A square root relationship of energy intensity reduction by CAV technology advance, i.e., CAV technology advance raised to the power of 0.5.	Assumption

Initial CAV CS travel cost	£/trip	8.536	Initial CAV car/ride sharing travel cost	Taxi How Much (2022).
Initial R&D investment	£ million/year	1200	Initial R&D investment on CAV technology development	Efrati (2020); Assumption
Initial CAV PC added purchase cost	£	16330	Initial extra purchase cost of a CAV private car as compared to a conventional private car.	Shabanpour et al. (2018)
Non CAV PC purchase cost	£	23185	Purchase cost of an average conventional private car	NimbleFins (2021)
Initial CAV PC usage cost	£/trip	5.2	Initial CAV private car usage cost	Department for Transport (2021b); NimbleFins (2021)
Initial CAV PT travel cost	£/trip	2	Initial CAV bus travel cost	Price of First Bus single adult ticket for within West Yorkshire trip in 2021
Initial CAV CS travel time	Min/trip	16.86	Initial CAV car/ride sharing travel time	Department for Transport (2021a); Assumption
Initial CAV PC in vehicle time	Min/trip	11.86	Initial CAV private car in-vehicle travel time	Department for Transport (2021a); Assumption

Initial CAV PC parking time	Min/trip	5	Initial CAV private car parking time	INRIX (2017); Assumption
Initial CAV PT in vehicle time	Min/trip	29	Initial CAV bus in-vehicle travel time	Transport for London (2022); Assumption
Initial CAV PT wait time	Min/trip	10	Initial waiting time for CAV bus	Assumption
Initial CAV PT walk time	min	10	Initial time for walking to and from CAV bus stops	Assumption
Initial network flow	vehicle/h/lane	259	Initial network flow on average roads	Department for Transport (2021a); Highways Agency (2002)
Initial network speed	Km/h	40.7	Initial network speed on average roads	Department for Transport (2021a)
Intervention CAV CS travel cost	£/trip	-3/-0.5/0	Interventions to change CAV car/ride sharing travel cost in different scenarios	Scenario control
Intervention CAV CS travel time	Min/trip	-2/-1.5/0	Interventions to change CAV car/ride sharing travel time in different scenarios	Scenario control
Intervention CAV PC travel cost	£/trip	-0.5/0/2	Interventions to change CAV PC travel cost in different scenarios	Scenario control

Intervention CAV PC travel time	Min/trip	-1.5/0/3	Interventions to change CAV PC travel time in different scenarios	Scenario control
Intervention CAV PT travel cost	£/trip	-1/-0.5/-0.25	Interventions to change CAV PT travel cost in different scenarios	Scenario control
Intervention CAV PT travel time	Min/trip	-15/-10/-5	Interventions to change CAV PT travel time in different scenarios	Scenario control
Intervention R&D investment	£ million/year	0/1200	Interventions to change R&D investment in different scenarios	Scenario control
learning elasticity	dml	0.5	With a learning elasticity of 0.5, every doubling of technological advance can reduce cost by around 30%.	Nieuwenhuijsen et al. (2018); Assumption
Knowledge transfer from investment	1 / million £	0.00001	With per 1 million R&D investment, CAV technology advance increase by 0.00001	Assumption
Marketing campaign	dmnl	0/1	Dummy variable of whether to have marketing campaign	Scenario control
Marketing effect	dmnl	0.3	Marketing campaign can increase innovation effect (coefficient p) by up to 30%	Assumption
Non CAV weight CS	dmnl	0.056	Percentage of car/ride sharing users in the non-CAV option	Department for Transport (2021c); Statista (2021); Assumption

Non CAV weight PC	dmnl	0.775	Percentage of private car users in the non-CAV option	Department for Transport (2021c); Statista (2021); Assumption
Non CAV weight PT	dmnl	0.169	Percentage of bus users in the non-CAV option	Department for Transport (2021c); Statista (2021); Assumption
Number of users per CS	person	100	Number of users each CAV car/ride sharing vehicle can serve	Monitor Deloitte (2017); Statista (2021); Assumption
Number of users per PC	person	1.5	Number of users each CAV private car can serve	Department for Transport (2020a); Office for National Statistics (2021)
Number of users per PT	person	261	Number of users each CAV bus vehicle can serve	Department for Transport (2020b, 2021c); Office for National Statistics (2020)
PC lifespan trips	dmnl	40000	Number of 5-mile trips an average private car can travel over its lifespan.	Ford, D. (2012).
R&D investment from CAV CS market	£ million/year	480	Additional R&D investment from CAV car/ride sharing market of up to 480 million per year, when all the population are CAV car/ride sharing users	Assumption
R&D investment from CAV PC market	£ million/year	2400	Additional R&D investment from CAV private car market of up to 2400 million per year, when all	Assumption

			the population are CAV private car users	
R&D investment from CAV PT market	£ million/year	240	Additional R&D investment from CAV bus market of up to 240 million per year, when all the population are CAV bus users	Assumption
Speed increase by CAV	Dmnl	0.06	The extent of road speed increase is up to 6% when all vehicles are CAVs	Stanek et al. (2017)
Tech advance effect on imitation	dmnl	0.3	Technology advance can increase imitation effect (coefficient q) by up to 30%, as an overall effect through perceived safety, perceived usefulness, perceived ease of use etc.	Assumption
Tech advance effect on innovation	dmnl	0.3	Technology advance can increase innovation effect (coefficient p) by up to 30%, as an overall effect through perceived safety, perceived usefulness, perceived ease of use etc.	Assumption
Time reduction extent CS waiting tech advance	dmnl	0.2	The extent of CAV car/ride sharing travel time reduction by CAV technology advance through waiting time reduction is up to 20%.	Assumption
Time reduction extent PC parking tech advance	dmnl	0.8	The extent of CAV private car parking time reduction by CAV technology advance is up to 80%	Assumption

Time reduction extent PT wait walk tech advance	dmnl	0.5	The extent of CAV bus waiting time and walking time reduction by CAV technology advance is up to 50%	Assumption
Time reduction power CS waiting tech advance	dmnl	0.5	A square root relationship of CAV car/ride sharing travel time reduction by CAV technology advance through waiting time reduction, i.e., CAV technology advance raised to the power of 0.5.	Assumption
Time reduction power PC parking tech advance	dmnl	0.5	A square root relationship of CAV private car parking time reduction by CAV technology advance, i.e., CAV technology advance raised to the power of 0.5.	Assumption
Time reduction power PT wait walk tech advance	dmnl	0.5	A square root relationship of CAV bus waiting time and walking time reduction by CAV technology advance, i.e., CAV technology advance raised to the power of 0.5.	Assumption
Total population	person	67,220,000	Total population in the UK in 2020	World Bank (2022)
Training campaign	dmnl	0	Dummy variable of whether to have training campaign	Scenario control
Training effect	dmnl	0.3	Training campaign can increase imitation effect (coefficient q) by up to 30%	Assumption

VMT change due to CS	dmnl	0.9	CAV car/ride sharing can reduce VMT by up to 10% (i.e., reduce to 90% of base level) when all CAV car users are CAV car/ride sharing users	Wadud et al. (2016); Assumption
VMT change due to PT	dmnl	0.15	CAV bus can reduce VMT by up to 85% (i.e., reduce to 15% of base level) when all the population are CAV bus users	Department for Transport (2021d, 2021e, 2021f, 2021g)
VMT change due to travel cost and new users	dmnl	1.42	Due to travel cost reduction and new user groups, CAVs can increase VMT by up to 42% (i.e., increase to 142% of base level) when all the population are CAV car users, which include CAV private car users and CAV car/ride sharing users	Wadud et al. (2016); Assumption

Model variable equations

Table 9.2 - Model variable equations

Variable	Unit	Equation
% CAV in total fleet	dmnl	= Fleet size of CAVs / Fleet size of all vehicles
% choose CAV CS	dmnl	= exp(CAV CS utility) / (exp(CAV CS utility) + exp(CAV PC utility) + exp(CAV PT utility) + exp(non CAV utility))
% choose CAV PC	dmnl	= exp(CAV PC utility) / (exp(CAV CS utility) + exp(CAV PC utility) + exp(CAV PT utility) + exp(non CAV utility))
% choose CAV PT	dmnl	= exp(CAV PT utility) / (exp(CAV CS utility) + exp(CAV PC utility) + exp(CAV PT utility) + exp(non CAV utility))
% PC users	dmnl	= (Number of CAV PC users + Number of non CAV users* Non CAV weight PC) / Total population

% PT users	dmnl	= (Number of CAV PT users + Number of non CAV users* Non CAV weight PT) / Total population
% CAV users	dmnl	Number of CAV users / Total population
Average travel cost	£/trip	= (CAV CS travel cost*Number of CAV CS users+CAV PC travel cost*Number of CAV PC users+CAV PT travel cost*Number of CAV PT users +Non CAV travel cost*Number of non CAV users)/Total population
Average travel time	Min/trip	= (CAV CS travel time*Number of CAV CS users+CAV PC travel time*Number of CAV PC users+CAV PT travel time*Number of CAV PT users +Non CAV travel time*Number of non CAV users)/Total population
Carbon emission	dmnl	= VMT * Energy intensity
CAV CS utility	dmnl	$=\beta_{tt}$* CAV CS travel time + β_{tc}* CAV CS travel cost + ASC CS
CAV PC utility	dmnl	$=\beta_{tt}$* CAV PC travel time + β_{tc}* CAV PC travel cost + ASC PC
CAV PT utility	dmnl	$=\beta_{tt}$* CAV PT travel time + β_{tc}* CAV PT travel cost + ASC PT
CAV CS travel cost	£/trip	Initial CAV CS travel cost * (1 - CAV CS travel cost reduction tech advance) * (1 - CAV CS travel cost reduction user number) + Intervention CAV CS travel cost
CAV CS travel cost reduction tech advance	dmnl	Cost reduction extent CS tech advance*(1- (CAV technology advance / Initial value of CAV technological advance)^(-learning elasticity))
CAV CS travel cost reduction user number	dmnl	Cost reduction extent CS user number*((Number of CAV CS users/Total population)^ Cost reduction power CS user number)
CAV CS travel time	Min/trip	(Initial CAV CS travel time / Speed change)* (1 - CAV CS travel time reduction waiting tech advance) + Intervention CAV CS travel time
CAV CS travel time reduction waiting tech advance	dmnl	Time reduction extent CS waiting tech advance *(CAV technology advance ^Time reduction power CS waiting tech advance)

CAV PC in vehicle time	Min/trip	Initial CAV PC in vehicle time / Speed change
CAV PC parking time	Min/trip	Initial CAV PC parking time *(1 - CAV PC parking time reduction tech advance)
CAV PC parking time reduction tech advance	dmnl	IF THEN ELSE (tech advance > 0.5, Time reduction extent PC parking tech advance *(CAV technology advance^Time reduction power PC parking tech advance, 0)
CAV PC purchase cost	£	Non CAV PC purchase cost + Initial CAV PC added purchase cost * ((CAV technology advance / Initial value of CAV technological advance)^(-learning elasticity))
CAV PC travel cost	£ / trip	CAV PC purchase cost/PC lifespan trips + CAV PC usage cost + Intervention CAV PC travel cost
CAV PC travel time	Min/trip	CAV PC in vehicle time + CAV PC parking time + Intervention CAV PC travel time
CAV PC usage cost	£ / trip	Initial CAV PC usage cost * (1 - CAV PC usage cost reduction tech advance)
CAV PC usage cost reduction tech advance		Cost reduction extent PC usage tech advance *(1 - (CAV technology advance / Initial value of CAV technology advance)^(-learning elasticity))
CAV PT fare reduction tech advance	dmnl	Cost reduction extent PT tech advance * (1 - (CAV technology advance / Initial value of CAV technology advance)^(-learning elasticity))
CAV PT fare reduction user number	dmnl	Cost reduction extent PT user number*((Number of CAV PT users/Total population)^ Cost reduction power PT user number)
CAV PT travel cost	£/trip	Initial CAV PT travel cost * (1 - CAV PT fare reduction tech advance) * (1 - CAV PT fare reduction user number) + Intervention CAV PT travel cost
CAV PT travel time	Min/trip	Initial CAV PT in vehicle time / Speed change + (Initial CAV PT wait time / Speed change)* (1 - CAV PT wait walk time reduction tech advance) + Initial CAV PT walk time * (1 - CAV PT wait walk time reduction tech advance) + Intervention CAV PT travel time

CAV PT wait walk time reduction tech advance	dmnl	Time reduction extent PT wait walk tech advance*(CAV technology advance^Time reduction power PT wait walk tech advance)
Energy intensity	dmnl	= 1 – energy intensity reduction * % CAV in total fleet *(CAV technology advance^Energy intensity reduction power tech advance)
Fleet size of All vehicles	vehicle	= Fleet size of CAV + Fleet size of non CAV
Fleet size of CAV	vehicle	= Fleet size of CAV CS + Fleet size of CAV PC + Fleet size of CAV PT
Fleet size of CAV CS	vehicle	= Number of CAV CS users / Number of users per CS
Fleet size of CAV PC	vehicle	= Number of CAV PC users / Number of users per PC
Fleet size of CAV PT	vehicle	= Number of CAV PT users / Number of users per PT
Fleet size of non CAV	vehicle	= (Total population – Number of CAV users)*Non CAV weight PC / Number of users per PC + (Total population – Number of CAV users)*Non CAV weight CS/ Number of users per CS + (Total population – Number of CAV users)*Non CAV weight PT/ Number of users per PT
Imitation effect	1/year	= coefficient q * (1 + training effect*training campaign + Tech advance effect on imitation* CAV technology advance)
Innovation effect	1/year	= coefficient p*(1+ Marketing effect * Marketing campaign + Tech advance effect on innovation* CAV technology advance)
Network flow	vehicle/h/lane	= initial network flow *(Fleet size of All vehicles / initial fleet size of non-CAV)*VMT
Network speed	kph	=(48.5 – 30*network flow/1000)* (1 + Speed increase by CAV *% CAV in total fleet))
Non CAV travel cost	£/trip	(non CAV PC purchase cost + Initial CAV PC usage cost* PC lifespan trips)/ PC lifespan trips* Non CAV

		weight PC+ Initial CAV CS usage cost* Non CAV weight CS + Initial CAV PT travel cost* Non CAV weight PT
Non CAV travel time	Min/trip	(Initial CAV PC in vehicle time / Speed change + Initial CAV PC parking time) * Non CAV weight PC + Initial CAV CS travel time/ Speed change * Non CAV weight CS + ((Initial CAV PT in vehicle time + Initial CAV PT wait time) / Speed change + Initial CAV PT walk time)*Non CAV weight PT
Non CAV utility	dmnl	=β_{tt}* Non CAV travel time + β_{tc}* Non CAV travel cost + ASC non CAV
Number of CAV car users	person	Number of CAV CS users + Number of CAV PC users
Number of CAV users	person	Number of CAV CS users + Number of CAV PC users + Number of CAV PT users
Number of non CAV users	person	Total population - Number of CAV CS users - Number of CAV PC users - Number of CAV PT users
Rate of CAV CS user gain	Person/year	= Number of potential CAV users WtC * % choose CAV CS
Rate of CAV CS users reconsider choice	Person/year	= % CAV CS users reconsider choice * Number of CAV CS users
Rate of CAV PC user gain	Person/year	= Number of potential CAV users WtC * % choose CAV PC
Rate of CAV PC users reconsider choice	Person/year	= % CAV PC users reconsider choice * Number of CAV PC users
Rate of CAV PT user gain	Person/year	= Number of potential CAV users WtC * % choose CAV PT
Rate of CAV PT users reconsider choice	Person/year	= % CAV CS users reconsider choice * Number of CAV PT users

Rate of CAV technology development	1/year	(Initial R&D investment + ((Number of CAV CS users/Total population)^0.5)*R&D investment from CAV CS market + ((Number of CAV PC users/Total population)^0.5)*R&D investment from CAV PC market + ((Number of CAV PT users/Total population)^0.5)*R&D investment from CAV PT market + Intervention R&D investment) * Knowledge transfer from investment * (1 – CAV technology advance)
Rate of WtC gain	Person/year	= WtC gain by imitation + WtC gain by innovation
Speed change	Dmnl	= Network speed / Initial network speed
Traffic accidents	dmnl	= (1 – Accident reduction*Pct CAVs in total fleet*(CAV technology advance^ Accident reduction power tech advance))* VMT
VMT	dmnl	= VMT change due to travel cost and new users*number of CAV car users/total population*(VMT change due to CS * number CAV CS users/number of CAV car users +1 - number CAV CS users/number of CAV car users) + VMT change due to PT* number of CAV PT users / total population + (total population-Number of CAV users)/total population
WtC gain by imitation effect	Person/year	= Number of potential CAV users not yet willing to consider CAVs * imitation effect * Number of CAV users / Total population
WtC gain by innovation effect	Person/year	= Number of potential CAV users not yet willing to consider CAVs * innovation effect

Model level equations

Table 9.3 - Model level equations

Level	Unit	Initial value	Equation
CAV technology advance	dmnl	0.1	= INTEG(Rate of CAV technology development)
Number of CAV CS users	person	1	= INTEG(Rate of CAV CS user gain - Rate of CAV CS users reconsider choice)
Number of CAV PC users	person	1	= INTEG(Rate of CAV PC user gain - Rate of CAV CS users reconsider choice)
Number of CAV PT users	person	1	= INTEG(Rate of CAV PT user gain - Rate of CAV CS users reconsider choice)
Number of potential CAV users not yet willing to consider CAVs	person	67,219,996	= INTEG (-rate of WtC gain)
Number of potential CAV users willing to consider CAVs	person	1	= INTEG(rate of WtC gain – rate of CAV CS user gain - rate of CAV PC user gain - rate of CAV PT user gain + Rate of CAV CS users reconsider choice + Rate of CAV PC users reconsider choice + Rate of CAV PT users reconsider choice

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