Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow

Summary Report

Department for Transport

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Executive summary

The capability of CAVs is progressing at a great rate, with particular focus on technological performance, and much associated work around safety, operation and regulatory issues. Whilst useful, existing evidence is often limited in terms of scope, scale, approach or underlying assumptions, and has not sufficiently addressed questions about large-scale impacts on traffic flow and capacity which are required inform policy.

Whilst the potential impacts of connected and autonomous vehicles are wide ranging, this work is limited to **the impacts of changes in technology on traffic flow and measures of network performance**.

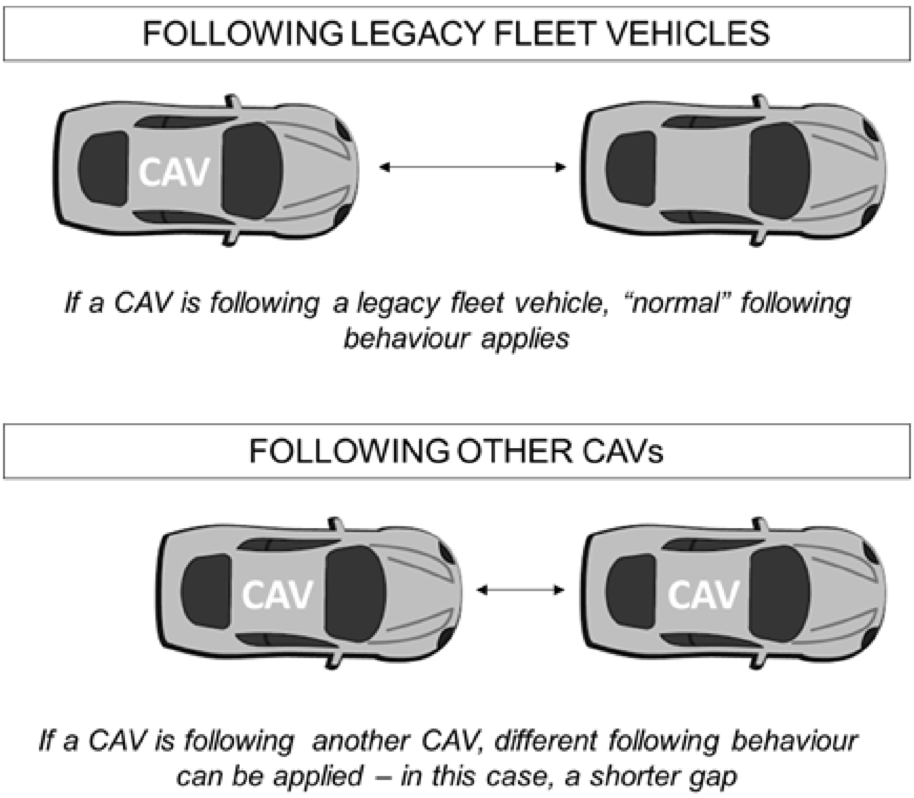
Microsimulation modelling

This work has utilised a prevalent microsimulation software package, VISSIM 8, to test the impact of:

- Different car-following behaviour;
- Different lane changing and gap acceptance behaviour;
- Different profiles of acceleration and deceleration;
- Connectivity to represent the better provision of information; and,
- Different levels of CAV penetration in the vehicle fleet.

As a first step, particular parameters were identified that allow the capabilities of connected and autonomous vehicles to be represented in the model. It is recognised that connected and autonomous vehicles may not exhibit “enhanced” behaviour across all aspects of operation. For example, whilst it is often assumed that CAVs will be able to travel at high speed and short time intervals, depending on the configuration and demands for safety, they may not. The capability of CAVs is likely to be dependent, at least in part, on user preference. CAVs are therefore characterised by their behaviour being either more assertive or more cautious than the default situation.

It is also recognised that CAVs may be configured to amend their behaviour. A methodology was therefore developed where following CAVs can alter their behaviour based on the characteristics of the lead vehicle, as demonstrated below.



Representative base networks

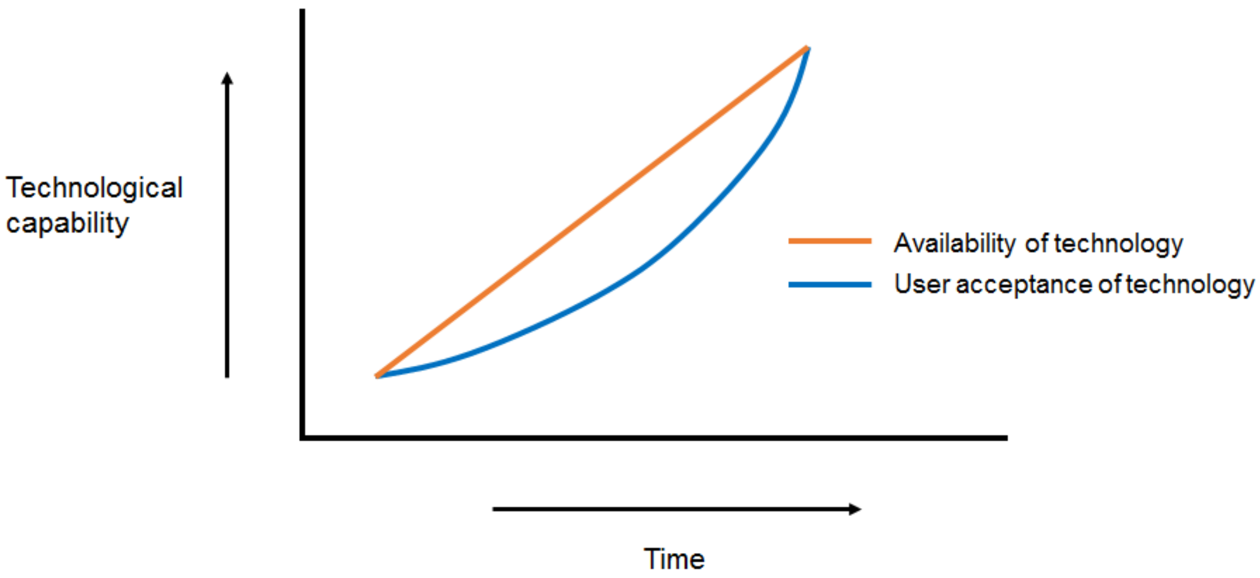
Two base traffic networks were constructed, designed to represent common situations on the strategic road network (SRN) and the urban road network. These include a variety of network elements, common to the UK road network, which allow a range of different behaviour types to be investigated.

Model	Network elements
SRN model	Motorway A-road Major intersection (free-flow) Major intersection (controlled) Merge and diverge
Urban model	Urban A-road Signalised junctions Mid-link pedestrian crossings Priority junctions Dedicated PT infrastructure

The models are designed to be representative of the UK road network, and are therefore not time, site or purpose specific.

Plausible future scenarios

The future of connected and autonomous vehicles is likely to be one of increasingly available technology. Whilst it is expected that this technology will have the potential to enhance vehicle operations to the benefit of network performance, this benefit may not be realised. Tensions around user confidence in technology and the trade-off between safety, comfort and network performance is likely to result in a **mix of different vehicle capabilities.**



To aid in this modelling work, a series of capabilities have been defined (Level I – Level IV) to reflect the changing make-up of the vehicle fleet.

Level I (No automation) is used to describe the base fleet of passenger cars and goods vehicles. The default parameters are assumed with no parameter variation.

Level II (Driver assistance) employs parameters relating to speed oscillation and throttle control. The capability provided in Level II will also be applied to Level III and Level IV vehicles.

Level III (Partial → high automation) incorporates automated longitudinal and lateral behaviour. This level recognises the role of user choice, with some vehicles adopting assertive behaviour, and some adopting cautious behaviour. This results in a mix of vehicle capabilities.

Level IV (Full automation) replicates the behaviour of Level III, with a key difference. The DfT's detailed review, "The Pathway to Driverless Cars", describes a fully automated CAV as a vehicle in which the driver is not necessary. In this instance it is assumed that the driver has no input to the driving task, and as such the vehicle *will* move with enhanced longitudinal and lateral behaviour.

In order to define **plausible future scenarios for the vehicle fleet**, the following things are taken into account:

- It is recognised that changes to vehicle capability will be incremental, with driver assistance and partial automation systems pervading initially;
- It is recognised that CAV penetration does not necessarily mean "enhanced" longitudinal and lateral behaviour with respect to traffic flow, network performance and road capacity – user choice will be a key determinant; and,
- It is recognised that a range of different CAV capabilities will be present in the vehicle fleet.

The scenarios used in this simulation testing are shown in the table below, applied to all vehicle types (passenger cars and goods vehicles) and in both network models. The theoretical 'upper bound' is a vehicle fleet consisting solely of assertive, fully automated vehicles.

Scenario	**CAV penetration** *Level II – IV*	***CAV penetration composition***		
		Level II Driver assistance	*Level III Mix of capability*	*Level IV Full automation*
Base	0%	*0%*	*0%*	*0%*
25% penetration (1)	25%	*20%*	*5%*	*0%*
50% penetration (2)	50%	*35%*	*10%*	*5%*
75% penetration (3)	75%	*50%*	*15%*	*10%*
100% penetration (4)	100%	*40%*	*20%*	*20%*
Upper bound (5)	100%	*0%*	*0%*	*100%*

Simulation results

The tables below summarise results for the SRN and urban models for the various CAV scenarios. The results shown here are for simulations have been carried out in a high demand situation, analogous to the peak period, and characterised by congestion, vehicle delay, low speeds and journey times.

Results for the strategic road network show a potential improvement in delay of more than 40%, assuming 100% penetration of assertive CAVs. There is an associated improvement in average journey time (for a particular route) and in the variability of journey time (as the standard deviation). These results also suggest a high penetration of CAVs is required to achieve significant benefits. With CAVs making up around 25% of the vehicle fleet, benefits are negligible.

SRN model results						
Scenario	**Average delay (s)**		**Average journey time (s)**		**Journey time variability[1] (s)**	
	(s)	**%**	**(s)**	**%**	**(s)**	**%**
Base	35.84	-	539.79	-	20.17	-
(1) 25% CAV	36.17	*+0.9%*	538.49	*-0.2%*	19.38	*-3.9%*
(2) 50% CAV	33.39	*-6.8%*	533.62	*-1.1%*	17.65	*-12.5%*
(3) 75% CAV	29.77	*-16.9%*	527.72	*-2.2%*	15.33	*-24.0%*
(4) 100% CAV	23.72	*-33.8%*	517.77	*-4.1%*	10.52	*-47.9%*
(5) Upper bound	21.38	*-40.3%*	479.29	*-11.2%*	9.14	*-54.7%*

Results for the urban model show a much greater improvement at low (25%) levels of CAV penetration, with a 12% improvement in delay, 21% improvement in journey times and a near 80% improvement in journey time.

This improvement in reliability is particularly high, and unlikely to be seen in all situations. However, testing these CAV scenarios in a low demand model, characterised by low congestion and higher average speeds, demonstrated an improvement in journey time reliability of around 30%, broadly supporting this conclusion.

Urban model results						
Scenario	**Average delay (s)**		**Average journey time (s)**		**Journey time variability (s)**	
	(s)	**%**	**(s)**	**%**	**(s)**	**%**
Base	65.91	-	277.78	-	88.38	-
(1) 25% CAV	57.70	*-12.4%*	219.52	*-21.0%*	19.74	*-77.7%*
(2) 50% CAV	54.44	*-17.4%*	205.35	*-26.1%*	10.01	*-88.7%*
(3) 75% CAV	51.89	*-21.3%*	198.72	*-28.5%*	7.24	*-91.8%*
(4) 100% CAV	48.02	*-27.1%*	192.64	*-30.7%*	6.00	*-93.2%*
(5) Upper bound	46.36	*-29.7%*	184.25	*-33.7%*	5.71	*-93.5%*

[1] Defined as the standard deviation

The impacts on traffic flow and network performance

Modelling the increasing presence and capability of connected and autonomous vehicles of the vehicle fleet yields results relating to network performance measures such as **delay** and **journey time**.

The potential for a decline in network performance, rather than improvements

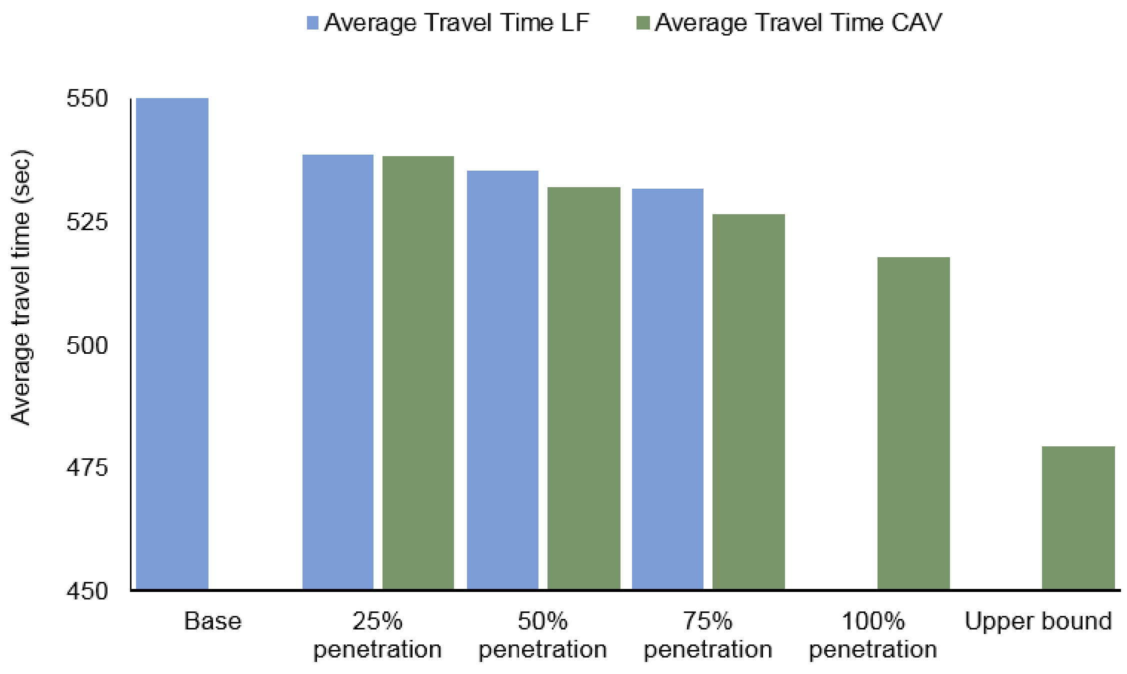
A review of literature highlighted the importance of user choice – it should not be assumed that CAVs will offer enhanced behaviour over the existing vehicle fleet. Accounting for user preference, comfort and safety, it is *plausible* that at least a section of the emerging CAV vehicle fleet is more cautious than that currently operating. This has been represented in the design of CAV scenarios, with early (low penetration) deployments of CAVs including a relatively high proportion of cautious vehicles. This may result in **detrimental changes to network performance**, especially in high-speed, high-flow situations (such as the SRN).

Substantial benefits may not be achieved until high levels of connectivity and automation

There is potential for significant benefits to network performance, particularly in high-speed, high-flow, congested situations. However, there is evidence that at low penetrations, any assertive CAVs are limited by the behaviour of other vehicles; that vehicles are not able to make use of their enhanced capability. This leads to suggestion of a tipping point – the proportion of enhanced vehicles required before major benefits are seen. This work suggests this may be between 50% and 75% penetration of CAVs. Results for the strategic road network model indicate improvements in delay of 7% for a 50% penetration of CAVs, increasing to 17% for 75% penetration and **as high as 40% for a fully automated vehicle fleet**. Furthermore, benefits are greatest in congested networks, which are constrained by level of traffic density that can be achieved.

Benefits are not constrained to one class of user

The increased capability of a subset of the fleet does not limit benefits to just those vehicles. Benefits are apparent for both CAVs and the unchanged legacy fleet, demonstrating that improvements can be expected for all network users.



Urban areas with lower speed limits may benefit most from low-tech driver assistance capability

The benefits to the strategic road network, where high-flow and high-speed situations prevail, are when vehicles can travel more closely spaced and maintain speed at a very high level of flow. Due to the traffic mix of motorised and non-motorised users, urban areas necessarily have a speed limit. There is therefore a limit to what can be achieved through more closely spaced vehicles. Low capability (and more immediately available) CAVs are termed to have "driver assistance" technologies. In this work, this has been characterised by better control of speed. This helps to maintain the spacing of vehicles and reduces unnecessary acceleration and decelerating operations. Results from the urban model suggest initial **benefits to delay of more than 12% with a 25% penetration of CAVs, rising to 30% with a fully automated vehicle fleet**.

Reliability is likely to improve

The major measures of network performance – such as journey time and delay – have been shown to generally improve with increasing penetration and capability of CAVs. However, there is also evidence that reliability will also improve[2]. Furthermore the scale of improvement in reliability far outweighs that shown in general performance – in the urban model in particular, **benefits of between 30% and 80% are shown with a 25% penetration of CAVs**, dependent on the demand situation.

Key questions for policy

There is inherent uncertainty associated with forecasting. Whilst grounded in previous work, it has been necessary to make a series of assumptions regarding the future penetration and capability of CAVs. This raises a series of key questions for policy makers, regarding **the capability available in CAVs** and the **penetration and uptake of CAVs**.

The capability of connected and autonomous vehicles will be tailored by automotive manufactures to the demands of the user. As the automotive industry is not charged with the safe and efficient operation of the road network, **maximum benefits to the performance of the network may not be obtained**. A key question for policy is therefore how best to facilitate CAVs (in terms of capability, penetration and uptake) in providing network-wide benefit. The transition period, where connectivity and autonomy of limited capability becomes embedded in the vehicle fleet, will be of key importance. This has clearly begun, with a high proportion of new vehicles having some form of this capability enabled.

There is also a need to consider how these fundamental changes to vehicle behaviour may impact the **demand for travel** and **car ownership**. On a basic level, more effective network capacity and efficient use of infrastructure will decrease the cost of travel, potentially inducing more vehicle trips. However, there are also more complex questions, including better understanding the value of travel time and changes in vehicle costs and mobility as a service (MaaS) may change models of car ownership. Rather than simply change the way vehicles operate on the road network, the ultimate future for CAVs may fundamentally alter the way in which people travel.

Any impacts on traffic flow are likely to also impact the **environment**, particularly in terms of vehicle emissions and air quality. The **safety** benefits of CAVs have been extolled, with a clear advantage from removing the potential for human error from the system. Understanding the potential impact of CAVs on these areas is essential in ensuring the **appraisal of transport schemes** is robust. This is particularly relevant in the case of major schemes with long appraisal periods, extending many years in the future, where connectivity and autonomy in the vehicle fleet is expected to be standard.

This work has considered two specific situations, for the SRN and an urban road network, with typical levels of network demand reflecting peak and off-peak times. Whilst this is a practical approach to inform policy, specific results relating to improvements in demand, journey time and capacity must be considered appropriate to the situations being modelled. The major contribution of this work is not in providing exact estimates of improvements to network performance, but in demonstrating the important mechanisms of action, and the potential benefits and constraints of step-changes in vehicle capabilities.

[2] Considered here as the standard deviation of modelled journey time

1. Introduction

The Department for Transport (DfT) have commissioned Atkins and White Willow Consulting to better understand the potential impacts of connected and autonomous vehicles (CAVs) on traffic flow and road capacity. This research project consists of two distinct phases:

- Stage 1 – an evidence review of the impacts of CAVs on traffic flow and road capacity; and,
- Stage 2 – analysis to quantify the potential impacts of CAVs on traffic flow.

This document summarises the findings of the project. It is supported by two detailed reports, the *Stage 1 Evidence Review* and the *Stage 2 Technical Report*. This report is divided into six chapters, containing the following elements:

- An introductory chapter, providing context and specifying the research objectives (Chapter 1);
- A review chapter, discussing the mechanisms of action and current understanding (Chapter 2);
- A methodology chapter, detailing the specific modelling approach undertaken (Chapter 3);
- Details of the future year scenarios to be modelled (Chapter 4);
- Results, including an explanation of the outputs and presentation methods (Chapter 5); and,
- Conclusions, limitations and recommendations for further work (Chapter 6).

This report is technical in nature, and assumes some familiarity with microsimulation modelling and traffic engineering. Terminology relating to connected and autonomous vehicles will be discussed in Section 1.2, with further technical aspects introduced throughout the report.

1.1. Context and objectives

The capability of CAVs is progressing at a great rate, with particular focus on technological performance, and much associated work around safety, operation and regulatory issues. Whilst useful, existing evidence is often limited in terms of scope, scale, approach or underlying assumptions, and has not sufficiently addressed questions about large-scale impacts on traffic flow and capacity which are required inform policy.

The potential impacts of connected and autonomous vehicles are wide ranging. These include, but are not limited to, the following broad subject areas:

- Safety and unplanned incidents;
- Travel demand and car ownership;
- Emissions, air quality and global climate change;
- Route planning, choice and in-vehicle navigation;
- Accessibility, travel choice and social inclusion;
- Provision of data for network operations and strategic planning; and,
- Link and junction capacity.

All of these areas have some potential to influence traffic flow, capacity and measures of road network performance. This work focuses on the microscopic behaviour of traffic, focusing on position (and derivations of position) of the driver-vehicle unit. The mechanisms by which improved technology, including enhancement to autonomy and connectivity, can influence vehicle behaviour, include:

- Vehicles may have changed accelerating and decelerating behaviour;
- Vehicles may have changed longitudinal behaviour when following other vehicles; and,
- Vehicles may have changed lateral behaviour when changing track.

For example, connected and autonomous vehicles may travel closer together, meaning higher density of traffic flow can be obtained, and greater capacity can be achieved through existing infrastructure.

This work does not consider higher order effects associated with this benefit to network performance. For example, greater capacity has the potential to induce additional trips, or result in a different distribution of trips across the road network. Whilst this potential is recognised, the purpose of this work is to consider changes to vehicle dynamics in isolation.

The objectives of this study are therefore to quantify the potential impacts of CAVs on traffic flow and measures of network performance. This will consider a range of road types, vehicle capabilities (autonomy and connectivity), market penetrations and demand situations. Whilst specific to the UK road network, the findings here are transferrable in an international context.

1.2. Definitions

It is recognised that multiple definitions are available concerning connected and autonomous vehicles. The DfT's detailed regulatory review, "The Pathway to Driverless Cars"[3] uses two broad definitions to describe **autonomous** and self-driving vehicles.

Highly automated – a driver is required to be present, and may need to take manual control of the vehicle. Under certain traffic, road or weather conditions, the vehicle's automation systems may request the driver to take control.

Fully automated – a driver is not necessary, with the vehicle capable of safely completing journeys in all normally encountered traffic, road and weather conditions. The enables occupants to spend their time on other activities during the journey.

Commonly referred to definitions for autonomy include SAE International's levels of driving automation[4], as shown below.

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

Source: SAE International J3016

These levels also make a distinction as to whether the human driver or the automated driving system monitors the driving environment. This is an aspect of connectivity.

[3] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/401562/pathway-driverless-cars-summary.pdf

[4] J3016

A **connected car** is one which is able to connect to external networks, whether it be other vehicles, infrastructure or general information provision. Some of the benefits of connected vehicles may be realised without a vehicle specific connection – for example, a driver with a mobile phone which provides information to the urban traffic network, or an in-car satellite navigation system that can provide live route information. A distinction is therefore often made between vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity.

For the purposes of this study, the existing vehicle fleet (which is necessarily defined as not being CAVs) are termed **legacy vehicles**. It is recognised that many aspects of connectivity are already prevalent on UK roads. These are not considered explicitly as part of the base situation.

2. CAVs, traffic flow and road capacity

This chapter discusses some of the expectations around connected and autonomous vehicles, particular around how they can influence traffic flow, network performance and road capacity. Further to this, discussion of the existing knowledge base is provided, culminating in the formation of priorities for modelling in this project, and some of the key questions for research in this field. This chapter is supported by the *Stage 1 Evidence Review* report.

Capacity is defined as the maximum sustainable flow of traffic passing in a single hour under favourable road and traffic conditions. This definition is consistent with UK standards (TA 79/99) for the traffic capacity of urban roads. **Headway** (the average time separation of vehicles) is related to capacity in that it is the reciprocal of traffic flow. **Delay** is generally calculated as the difference between the theoretical attainable travel time (taking into account road geometry) and the actual travel time. Further definitions will be given where relevant.

2.1. Mechanisms of impact

Technological advancements associated with connectivity and autonomy have the capability to change the way vehicles behave to the benefit of traffic flow and road capacity. These mechanisms are generally well understood and widely accepted. Some example of the potential for changed behaviour are shown in Table 1.

Table 1: Example mechanisms of CAV impact under different road network situations

Behaviour type	Description	Potential CAV impact on vehicle operation and network performance
Free driving	The vehicle responds only to the infrastructure (i.e. there is no other traffic)	Perfect throttle control – no oscillation around a desired speed Changed profiles of acceleration and deceleration
Vehicle following	The vehicle is following another vehicle in a single lane	Vehicles are able to travel at smaller time intervals, safely and at greater speed than currently
Lane changing	The vehicle changes lane in a multi-lane situation, either to maintain a desired speed or to prepare for a route decision	Vehicles are able to accept smaller gaps in traffic and manoeuvre safely between streams of traffic at greater speed
Merging and joining	The vehicle must join a dominant stream of traffic and avoid conflict	Vehicles cooperate to enable smooth merging of conflicting traffic streams, at higher speed and with smaller gaps
Planning and decision making	The vehicle must react to the behaviour of other vehicles, other road users or infrastructure	Better provision of data and communication between entities leads to better and more efficient decision making

Through a more efficient use of available road space, benefits may be achieved for both the user (individual travellers) and the network operator in terms of improved reliability, shorter journey times and less delay. There is a great deal of uncertainty over whether these benefits will be realised and, if they are, the magnitude of the benefits.

Considering the example of longitudinal spacing, network performance, road capacity and traffic flow would likely benefit if vehicles are able to safely travel closer to each other on a road. CAVs may be able to provide the technology to enable this, replacing the fallible human driver with precision control. In evaluating the potential benefits, a number of trade-offs must be considered:

Comfort, safety and capacity

The optimum setting for each of these three characteristics is unlikely to be aligned. Whilst it may be technically feasible for a vehicle to travel at speed only a few metres from the vehicle in front, this may not be acceptable according to the desires for comfort from the user. Alongside this, safety is likely to be an overarching constraint in any regulated environment.

User-optimal versus network-optimal

Automotive manufacturers are not charged with the safe, efficient and reliable operation of the road network. Within the confines of regulation, it will be these OEMs, and ultimately the market they serve, which will determine the capabilities of CAVs. This may not result in the same suite of capabilities had, for example, UK road network operators determined the requirements. Again, the balance between comfort, safety and capacity is likely to be key.

The following sections will discuss the current understanding around how CAVs may influence traffic flow and capacity, with particular consideration given to the longitudinal spacing of vehicles when following other vehicles, lateral movement of vehicles (for example, when changing lanes) and different behaviour at junctions.

2.2. Current understanding

This section draws on a broader literature review contained within the *Stage 1: Evidence Review* report. This is not an exhaustive account of research in this area, but serves to demonstrate the current state-of-the-art.

2.2.1. Vehicle following

Particular technologies are emerging or already in production that influence the longitudinal spacing of vehicles. Some examples are:

- Adaptive cruise control (ACC), where the vehicle automatically adjusts the gap (defined in time and/or space) to the vehicle in front, using passive sensor data to adjust speed; and,
- Connected adaptive cruise control (CACC), where the vehicle can also receive and act upon data from vehicles further ahead in the traffic stream.

In both these cases, the driver retains control over the lateral movement of the vehicle in terms of lane choice. In additional to enabling shorter spacing between vehicles, it has been reported that ACC and CACC could improve capacity by impacting “string stability” – reducing errors and differences in deceleration rates between vehicles which cause “shockwaves”.

Estimates of the benefits that can be achieved through enhanced longitudinal behaviour range greatly. For example, Tientrakool et al[5] calculated an approximate 43% increase in capacity with full (100%) penetration of ACC enabled vehicles. This study assumed gaps between vehicles of 1.1 seconds, made safe in conditions of highly aggressive braking. Similarly, studies such as Bierstedt et al[6] found that lane capacity could be as much as doubled in a scenario with short gaps between vehicles and aggressive accelerating and decelerating behaviour. This study also highlights the importance of fleet penetration – benefits were found to be marginal

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[5] Tientrakool, P., Ho, Y.C. and Maxemchuk, N.F., 2011. Highway capacity benefits from using vehicle-to-vehicle communication and sensors for collision avoidance. In Vehicular Technology Conference (VTC Fall), 2011 IEEE (pp. 1-5). IEEE

[6] Bierstedt, J., Gooze, A., Gray, C., Peterman, J., Raykin, L. and Walters, J., 2014. Effects of next-generation vehicles on travel demand and highway capacity. FP Think Working Group, University of Princeton pp.10-11

until a high proportion (>75%) of the fleet were equipped with technology to allow enhanced following. Arnaout et al[7] suggested that penetration of at least 40% of enabled vehicles is required before benefits are seen.

The key points for consideration are therefore:

- The time separation between vehicles;
- The rate at which acceleration and deceleration occurs; and,
- The penetration of enabled vehicles in the fleet.

Neither of these quantities are well understood at present. Time gaps adopted in studies to date range from approximately 0.5s to 2.0s – greater than a typical human driver. Any attempt at quantifying the traffic flow and capacity impacts of vehicles with changed longitudinal behaviour should therefore consider a range of different scenarios.

Platooning is a particular example of connected adaptive cruise control where a single driver may be in control of an entire "road train", potentially also including their lateral (lane changing) behaviour. These are often thought of as platoons of HGVs only, but may include any equipped vehicles. A variety of studies have demonstrated potential benefits of platoons[8,9], above and beyond ACC and CACC could achieve when deployed in individual vehicles. However, these are only likely to be realised if a large number of vehicles join a platoon, including passenger cars. Platoons are therefore likely to offer significant benefit to users – such as commercial freight operators – but may not impact substantially upon network capacity as a whole, especially during congested periods.

2.2.2. Behaviour at junctions and gap acceptance

Vehicles must identify a suitable gap in order to move between traffic streams, whether this is a simple lane-change, or a common conflicting movement such as a motorway merge or priority junction. The benefits of connected and autonomous vehicles may be to reduce this level of gap acceptance and better enable cooperative behaviour between vehicles on conflicting paths. Conversely, other work has suggested that[10] technologies to assist in motorway or expressway driving (such as ACC) may impact capacity in merge or lane-drop situations, creating a bottleneck. This brings out a clear point; there is likely a trade-off where technologies designed to assist the driver and improve the driving experience in a given situation may negatively impact operations in another situation.

Research[11] has indicated the potential for better provision of data – i.e. through connected vehicles – can reduce delays by encouraging early merging at junctions. Conversely, there is some evidence that automated vehicles behaviour, especially when pulling away at a signal junction, may reduce capacity. This is particularly the case if the behaviour of the vehicle, reflecting the preference of the user, is designed for comfort and safety, rather than traffic flow and road network capacity. Le Vine et al[12] investigated the interaction between user experience and capacity at a signalised intersection. Assuming the level of comfort required to be the same as experience on high speed rail, reductions in capacity of between 21% and 54% were shown (at 25% fleet penetration). This work does not assume connectivity between vehicles, which may be of key importance; if a CAV has to assume a human driven vehicle may unexpectedly decelerate at its maximum rate, the requirement for large headways may naturally follow.

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[7] Arnaout, G. and Bowling, S., 2011. Towards reducing traffic congestion using cooperative adaptive cruise control on a freeway with a ramp. Journal of industrial Engineering and Management, 4(4), pp.699-717.

[8] Chan, E., Gilhead, P., Jelinek, P., Krejci, P. and Robinson, T., 2012. Cooperative control of SARTRE automated platoon vehicles. In 19th ITS World Congress, Vienna, Austria, pp. 22-26

[9] Harwood, N. and Reed, N., 2014. Modelling the impact of platooning on motorway capacity. IET RTIG Conference 2014

[10] Davis, L.C., 2007. Effect of adaptive cruise control systems on mixed traffic flow near an on-ramp. Physica A: Statistical Mechanics and its Applications, 379(1), pp.274-290

[11] Park, H. and Smith, B.L., 2012. Investigating benefits of intellidrive in freeway operations: Lane changing advisory case study. Journal of Transportation Engineering, 138(9), pp.1113-1122

[12] Le Vine, S., Zolfaghari, A. and Polak, J., 2015. Autonomous cars: The tension between occupant experience and intersection capacity. Transportation Research Part C: Emerging Technologies, 52, pp.1-14

2.2.3. Key knowledge gaps

The comprehensive literature review (detailed in *Stage 1: Evidence Review*) identified a series of knowledge gaps that should be considered priorities for future research. Some of these offer particular opportunities for quantitative analysis through traffic modelling.

User preference

A multitude of research has demonstrated the potential for connected and autonomous vehicles to impact capacity on links and junctions through various mechanisms. Given the formative state of the CAV industry, work conducted previously has tended to be founded on a series of assumptions around, for example, time gap and acceleration rate. Plausible futures regarding what a connected or autonomous vehicle may be capable of do not necessarily translate into the desires of the user. It is therefore important to consider the heterogeneity of user choice in the vehicle fleet.

Vehicle fleet heterogeneity

Many studies consider an idealistic future state of connected and autonomous vehicles, with high penetration (tending towards 100%) and of enhanced capability. Whilst this is a likely situation at some point, it does not tackle the transition from the existing vehicle fleet to a fully autonomous one.

A more pertinent question for transport planners is concerned with the short term, where a low penetration of (potentially) low capability CAVs are mixed with the existing vehicle fleet. This must account for elements of user preference and capacity/comfort trade-offs previously discussed, as well as different user classes – passenger cars, HGVs and public transit vehicles.

The operational environment

Research into the physical characteristics of a vehicle is, of course, transferrable. However, much of the uncertainty around the behaviour of connected and autonomous vehicles is concerned with particular situations. The variety of operational traffic situations in the UK is such that specific research is required, as the types of behaviour (and therefore potential impacts) at roundabouts, free-flow motorway merges and signalised intersections is markedly different.

2.3. Summary

The mechanisms by which connected and autonomous vehicles could impact network performance, traffic flow and capacity are broadly accepted, including:

- Changed longitudinal following behaviour;
- Changed gap acceptance and merging behaviour;
- Changed profiles of acceleration and deceleration;
- Improved decision making due to better provision of information; and,
- Cooperative driving for user and network benefit.

These have been considered in a variety of studies, all of which contribute towards the wider problem. This work can build upon this previous body of work through considering a range of capabilities and penetration levels for UK-specific situations.

3. Modelling CAVs

Chapter 2 explained the mechanisms by which CAVs are expected to influence the operation of vehicles, and therefore impact measures concerning traffic flow, road capacity, vehicle delay and journey time. This chapter translates the objectives for the study and these mechanisms into a methodological approach. This chapter is supported by the *Stage 2 Traffic Modelling and Analysis Technical Report*.

3.1. Microsimulation modelling

Traffic microsimulation models represent the behaviour of individual vehicles on a road network. They model the interaction of vehicles with other vehicles, with the road network (for example, response to changing gradients and road geometry) and with traffic control systems.

3.1.1. Representation of traffic

The basis of traffic microsimulation software is a series of mathematical models, providing a set of logical rules to control the behaviour of the vehicle.

For example, car-following logic determines the interaction of a vehicle with the preceding vehicle in the same lane[13]. Generally the behaviour is classified as "following" when the trailing vehicle's behaviour is somehow constrained by the lead vehicle[14]. These models therefore use a series of physical characteristics of both vehicles – such as length, speed, desired speed and acceleration – alongside a series of constants that control the operation of the vehicle – such as the minimum allowed time gap between vehicles.

So that these models can be used to replicate microscopic behaviour in a given situation, the software implementation generally makes use of user-defined parameters which can be used for calibration.

3.1.2. VISSIM 8

VISSIM is a particular microscopic model of driver and vehicle behaviour. The model is largely deterministic – relying on a series of logical rules, including the Wiedemann model of car-following behaviour. However, there is also a stochastic element, allowing the model to reflect the inherent uncertainty associated with traffic. The latest version is VISSIM 8.

The basic requirements of a microsimulation software package suitable for this study are:

- The ability to represent the longitudinal and lateral behaviour of vehicles;
- Incorporation of a stochastic element;
- A model suitable for use in representing the UK road network; and,
- The ability to adapt the behaviour of vehicles to represent CAVs.

In VISSIM, vehicles are able to move laterally and/or longitudinally. Suitable parameters were identified which would allow for the representation of the modified behaviour of connected and autonomous vehicles in VISSIM, making it a suitable tool for this study. This will be discussed further in Section 3.2, and are covered in more detail in Limitations of this approach.

3.1.3. Limitations of microsimulation

Microsimulation models are generally used for input into design and appraisal of traffic schemes. The major aim is therefore to produce representative measures of macroscopic traffic flow– delay, journey time, flow and speed. This is an area in which microsimulation has proven to be a valuable tool.

The behaviour of individual vehicles is not generally considered in detail. As such the fidelity of the base situation – including, for example, the longitudinal spacing of vehicles, does not fall under scrutiny, and is not subject to site-specific calibration or validation.

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[13] Olstam, J.J. and Tapani, A., 2004. Comparison of Car-following models. Swedish National Road and Transport Research Institute.–2004.–45 c

[14] For example, if travelling at the desired speed would cause a collision

Furthermore, as microsimulation models are largely deterministic, they are not generally useful in replicating incidents, errors and accidents on the network. If benefits of CAVs are perceived to be due to reduced instances of driver error, these should be quantified via an alternative method.

3.2. CAV modelling methodology

This section discusses the exact methodology identified for the representation of CAVs. This covers the parameter selection as related to longitudinal movement, acceleration and deceleration, lateral movement and gap acceptance, and connectivity. The methodology is discussed further in the *Stage 2 Technical Report*.

3.2.1. Parameter selection

Particular VISSIM parameters have been identified as levers – allowing the modification of vehicle behaviour to represent a plausible future for CAVs. Behavioural change in VISSIM refers to a specific vehicle type. Whilst the generic term "vehicle" is used here, this could equally apply to passenger cars, goods vehicles or public transport vehicles.

Longitudinal movement

Longitudinal movement in VISSIM utilises the Wiedemann psycho-social model of behaviour. The driver-vehicle unit is assumed to be in one of four driving modes – free driving, approaching, braking and following. These are described in Table 2.

Table 2: Longitudinal movement behaviour in VISSIM (adapted from VISSIM documentation)

Driving mode	Description
Free driving	No influence of preceding vehicles observable. Vehicle-driver unit seeks to reach and maintain a desired speed. Actual speed oscillates around desired speed due to imperfect throttle control.
Approaching	The process of adapting the vehicle-driver unit speed to the lower speed of a preceding vehicle. While approaching, a vehicle-driver unit applies a deceleration so that the speed difference of the two vehicles is zero when the desired safety distance is achieved.
Braking	The application of medium to high deceleration rates if the distance falls below the desired safety distance. This can happen if the preceding car changes speed abruptly, of if a third car changes lanes in front of the observed driver.
Following	The vehicle-driver unit follows the preceding car without any conscious acceleration or deceleration. The safety distance is approximately constant, but due to imperfect throttle control and imperfect estimation the speed difference oscillates around zero.

Switching between modes for a vehicle-driver unit is governed by a threshold which can be described as a combination of the difference in speed between that and the preceding vehicle, and the distance between that and the preceding vehicle.

These behaviours are formalised as parameters in the **car-following model** and the **acceleration and speed function and distribution** components of VISSIM.

Lateral movement of vehicles

Lateral movement in VISSIM incorporates behaviour within (termed "lateral behaviour") and between (termed "lane change") lanes. Overtaking within lanes is permitted within VISSIM if sufficient space is available. For the purposes of this project, it is assumed that one vehicle occupies the effective full width of a single lane[15]. There are two types of lane changing behaviour replicated – necessary lane changes (for example, due to routing) and free lane changes (to take advantage of higher speeds and greater lane capacity).

Lateral movement incorporates longitudinal behavioural change in that the desired safety distance must be achieved/maintained as part of the manoeuvre. The "aggressiveness" of behaviour can be adapted for necessary lane changes through a series of available parameters.

Connectivity

There is no explicit representation of vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) within standard microsimulation modelling. Connectivity in this instance can be conceptualised as having better information with which to make decisions concerning longitudinal and lateral behaviour.

The parameters identified for use in this work are included in Appendix A

3.2.2. Dynamic behaviour change

In order to proxy potential vehicle-to-vehicle and vehicle-to-infrastructure connectivity, vehicles in the model must be able to change their behaviour *dynamically* according to the information of the surrounding environment. As traditional microsimulation environment does not provide such feature, the VISSIM COM interface is utilised in this case.

VISSIM COM (Component Object Model) Interface is an API (application program interface) that allows access to a VISSIM model through programming languages outside of the graphical user interface. Information relating to the entire network, including vehicle location, vehicle speed and vehicle behaviour can be obtained according to pre-determined algorithm.

This allows behaviour set applicable to the vehicle to be dynamic, dependent on a particular situation. For example:

- A vehicle may adopt different following behaviour based upon the preceding vehicle (e.g. utilise a shorter headway when following another CAV);
- A vehicle may adopt different (dynamic) routing decisions based on new information; or,
- A vehicle may adopt different free-driving behaviour based on a particular event exogenous to the model (e.g. a proxy for bad weather).

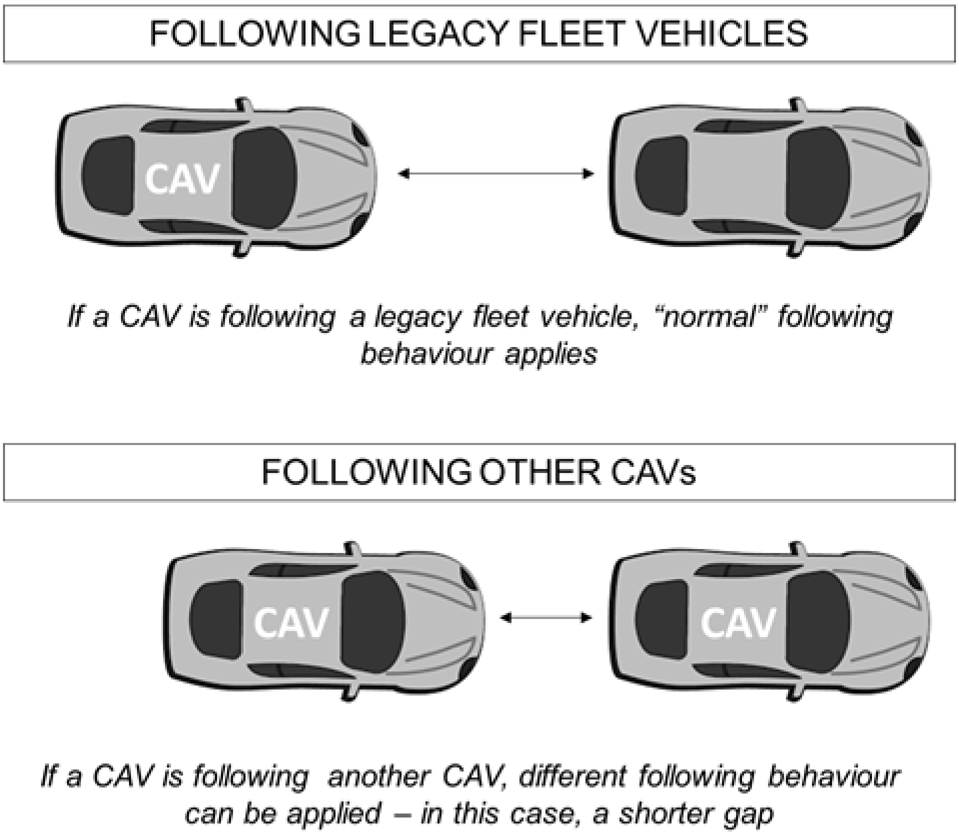
In this instance, the first approach has been used. It is expected that connected and autonomous vehicles will have the technical capability to enable following behaviour at very small time intervals. However, it is not necessarily expected that this will be utilised in all situations.

For example, Figure 1 demonstrates how different following behaviour can be applied depending on the preceding vehicle. In this simple example, the trailing CAV adopts different behaviour based on the characteristics of the lead vehicle.

The actual logic adapted as part of this study is explained in Chapter 4, with more detail included in the *Stage 2 Technical Report*.

[15] This is the general approach for microscopic modelling in the UK and the default behaviour in VISSIM

Figure 1: Connectivity and following behaviour



3.3. Parameter effects

In order to refine the proposed methodology, the effects of different parameter changes have been tested in a number of simple microsimulation models. The scope of these models is shown in Table 3, with exact details of the work carried out included in the *Stage 2 Technical Report.*

Table 3: Scope of simple models

Identifier	Model type	Behaviour focus
A	Single-lane link	Longitudinal gap
B	Multi-lane link	Longitudinal gap Lateral movement / gap acceptance
C	Signalised junction	Acceleration (+ve, -ve) Longitudinal gap
D	Roundabout	Lateral movement / gap acceptance Acceleration (+ve, -ve) Longitudinal gap
E	Multi-lane link with merge	Longitudinal gap Lateral movement / gap acceptance Acceleration (+ve, -ve)

These models were used with a range of CAV capabilities and levels of traffic demand. For example, Model A is a simple single-lane link. In order to test the impacts of changed longitudinal behaviour, a series of "capability levels" were defined. Level 1 represents a "cautious" CAVs – this assumes that future connected and autonomous vehicles drive with more safety and user comfort as the primary considerations, meaning they are spaced further apart than conventional vehicles. Level 9 represents "assertive" CAVs – this assumes that future CAVs are configured for performance more so that are spaced more closely together than the existing vehicle fleet.

Figure 2: Approach to varying CAV capability

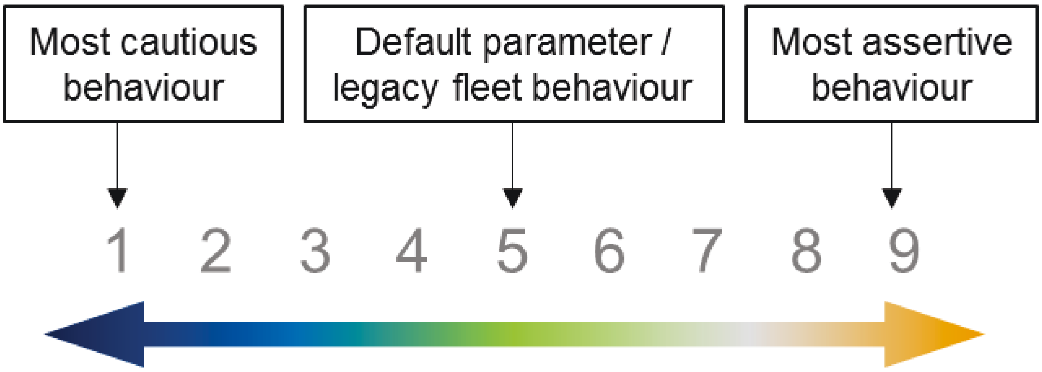
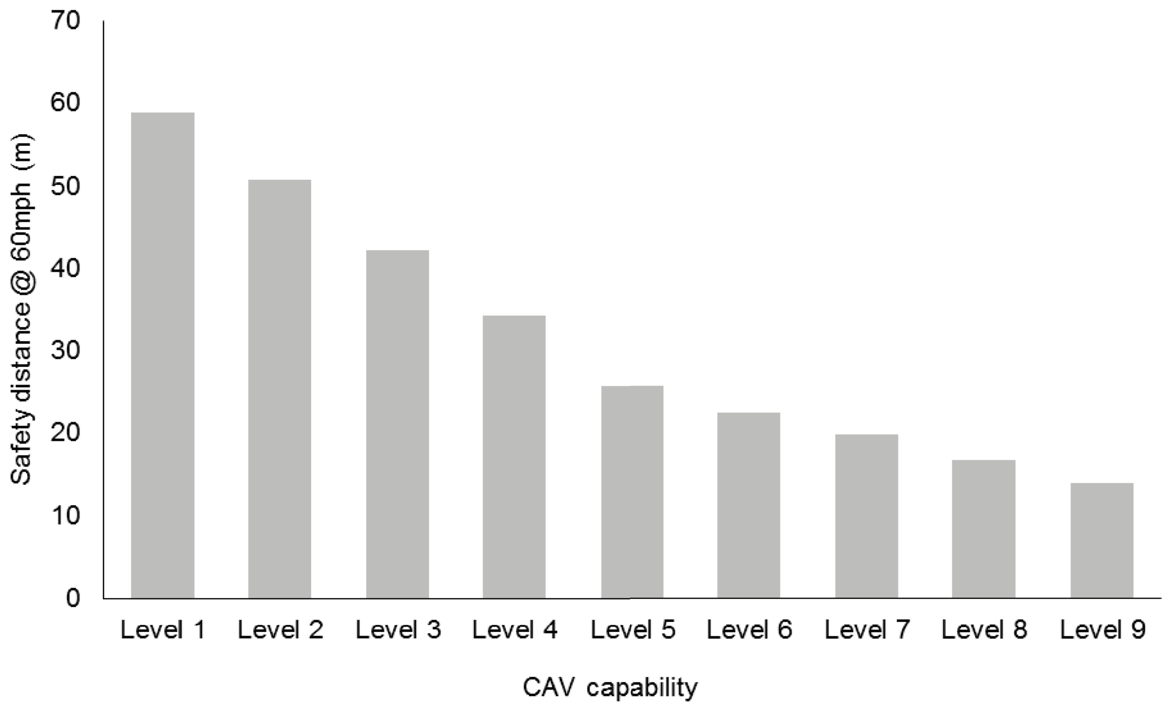


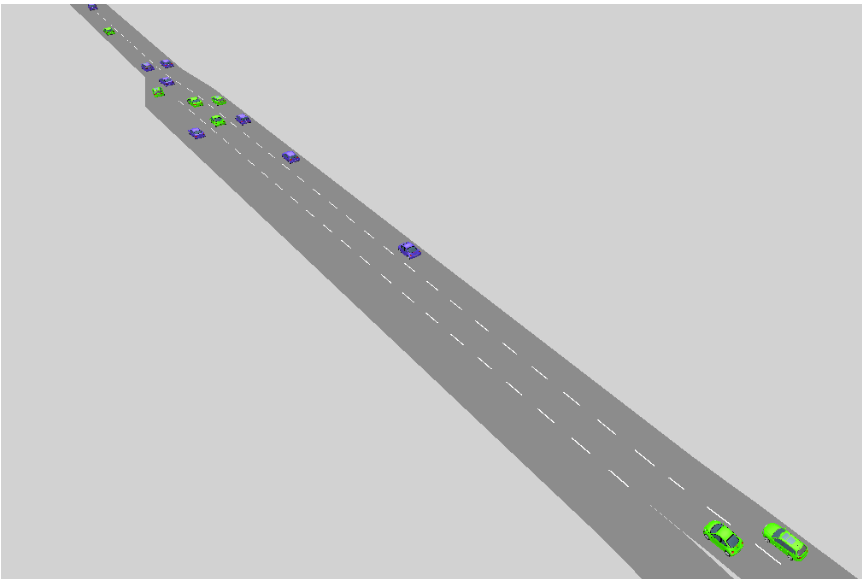
Figure 3 shows how these levels relate to a measurable characteristic. This figure shows the safety distance calculated at a speed of 60mph. This distance is a measure of the minimum (safe) distance vehicles will travel at in the microsimulation. In keeping with the findings of Stage 1, and discussed in Chapter 2 of this report, the headway between vehicles ranges from 0.5s to 2.1s.

Figure 3: Model A – CAV capability



The results obtained from these simulations cover a range of macroscopic traffic outputs – capacity, flow, speed and delay. An example for Model E is shown below. Model is a multi-lane link with merge (Figure 4).

Figure 4: Model E



This situation is a typical one on the UK strategic road network, with traffic from another stream joining a multi-lane link. Vehicles on the main carriageway follow other vehicles and may also overtake to attain their desired speed. Vehicles joining the main carriageway at the merge section must identify suitable and safe gaps. The model therefore looks at a range of different behaviours[16].

In this simple model, two aspects relating to CAVs are varied:

- The penetration of connected and autonomous vehicles (i.e. vehicles with changed behaviour); and,
- The capability of connected and autonomous vehicles (i.e. how assertive or cautious they are).

Table 4 shows the capacity impact of varying capability and penetration[17]. Capacity for each combination of capability and penetration is compared to the base situation – no CAVs. The results appear sensible, with greater penetration of increasingly capable CAVs resulting in greater capacity. Conversely, where CAVs are more cautious than the existing vehicle fleet, a decrease in capacity is observed.

Full details of these models, including a comprehensive set of results, are included in the *Stage 2 Technical Report*. Some useful conclusions have also been drawn:

- The results are mostly intuitive – smaller spacing and lower gap acceptance allow greater utilisation of the road space, higher road capacity, lower delays and decreased journey times;
- Improvements are not necessarily linear – twice the penetration of enhanced vehicles does not necessarily mean twice the capacity or network performance benefit;
- Benefits are smaller if the network is uncongested – improvements in network performance are more likely in peak times where traffic density is high; and,
- User choice is likely to be extremely important – if users prefer cautious vehicle behaviour, network performance may suffer.

[16] For these simple examples, no dynamic behavioural change capability has been included

[17] In order to assess capacity, demand is systematically increased; in order to represent stochasticity, 10 "random seeds" are used in VISSIM, with the average value taken

Table 4: Model E capacity impact

		Penetration of CAVs			
		25%	**50%**	**75%**	**100%**
Capability	**1**	-9.8%	-17.7%	-24.5%	-29.9%
	2	-6.8%	-12.6%	-18.0%	-22.1%
	3	-2.8%	-5.5%	-8.2%	-10.2%
	4	-0.1%	1.0%	2.1%	3.2%
	5	5.2%	11.6%	17.9%	23.8%
	6	8.2%	16.9%	25.7%	35.8%
	7	9.8%	20.0%	30.0%	43.3%
	8	12.3%	25.6%	39.5%	58.7%
	9	13.9%	28.3%	44.2%	67.3%

3.4. Method summary

The general approach adopted for this study is to proxy the effects of connected and autonomous vehicles in an existing traffic microsimulation software package. VISSIM 8 has been identified as a suitable software, with levers available to modify the following and lane changing behaviour of vehicles.

These behaviours have been tested in a series of basic models, demonstrating the effect of parameter changes in simple traffic situations.

Furthermore, a methodology for broadly representing connectivity has been developed, allowing for a CAV to adopt different behaviour dependent on the situation.

In the remaining chapters of this report:

- Chapter 4 discusses the plausible future scenarios of CAV deployment and the base traffic networks to be tested;
- Chapter 5 covers the results of the simulation model runs; and,
- Chapter 6 discusses the conclusions of this work and makes recommendations for further research.

4. Future CAV scenarios

4.1. Base traffic networks

This work considers two specific UK situations. These models are not designed to be site, time or purpose specific, but provide a base demonstrably fit for the purposes of this work.

Two models have been designed:

- An SRN model, designed to explore the interactions of CAVs and the legacy vehicle fleet in situations common to the UK strategic road network (Model F); and,
- An urban model, designed to explore the interactions in situations relating to urban A-roads (Model G).

Table 5 shows the scope of these models and the different network elements included.

Table 5: Base model network elements

Identifier	Model type	Network elements
F	SRN model	Motorway A-road Major intersection (free-flow) Major intersection (controlled) Merge and diverge
G	Urban model	Urban A-road Signalised junctions Mid-link pedestrian crossings Priority junctions Dedicated PT infrastructure

4.1.1. SRN model (F)

Model F considers the impacts of CAVs on the strategic road network, consisting of a 20km expanse of motorway connecting three junctions including common types of merge and diverge arrangements. This includes lane gains and lane drops, and more conventional slips road requiring lane change.

An overview of the model is shown in Figure 5. The modelled network includes the following junctions:

1. A free-flow motorway to motorway interchange (Figure 6);
2. A partially signalised grade separated roundabout without grade separated through movements (Figure 7); and,
3. A fully signalised grade separated roundabout including grade separated through movements (Figure 8).

The model also includes a section of dual carriageway A-road (expressway standard) and reduced speed dual carriageway approaches. This model is approximately based on J10 to J15 of the M25, particularly in terms of link alignment and junction layouts. In order to make this model more applicable to the wider UK strategic road network, fewer lanes have been modelled.

Figure 5: Overview of Model F, SRN, including major junctions

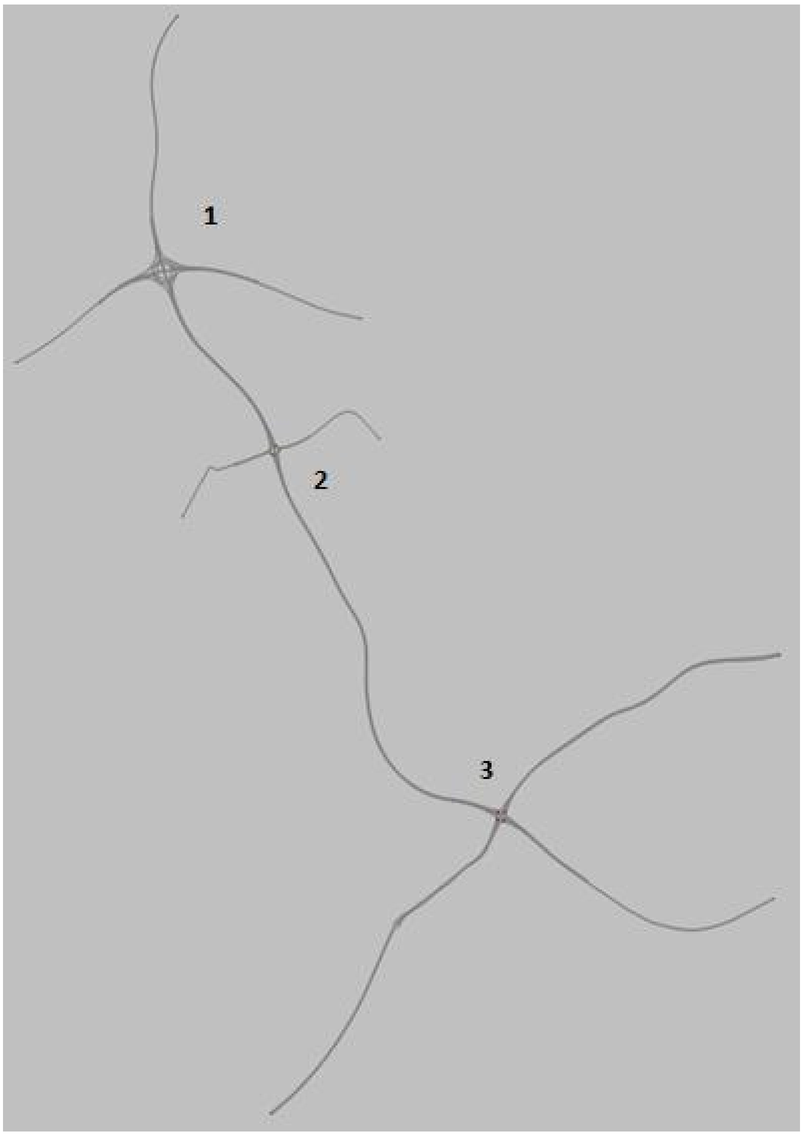


Figure 6: Free-flow interchange

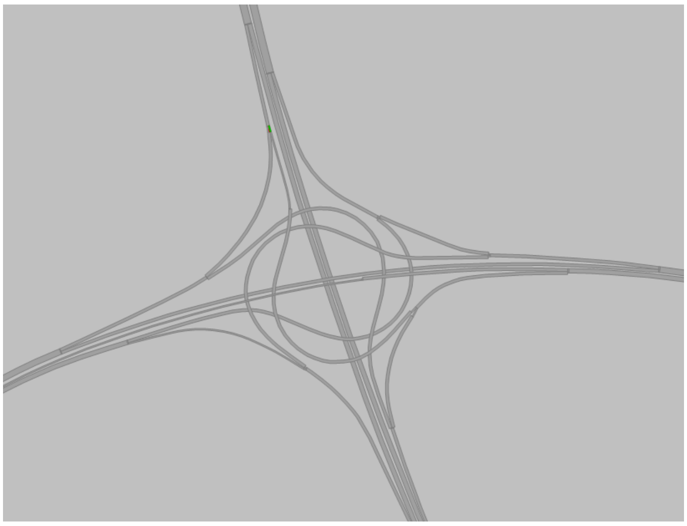


Figure 7: Partially signalised grade separated roundabout

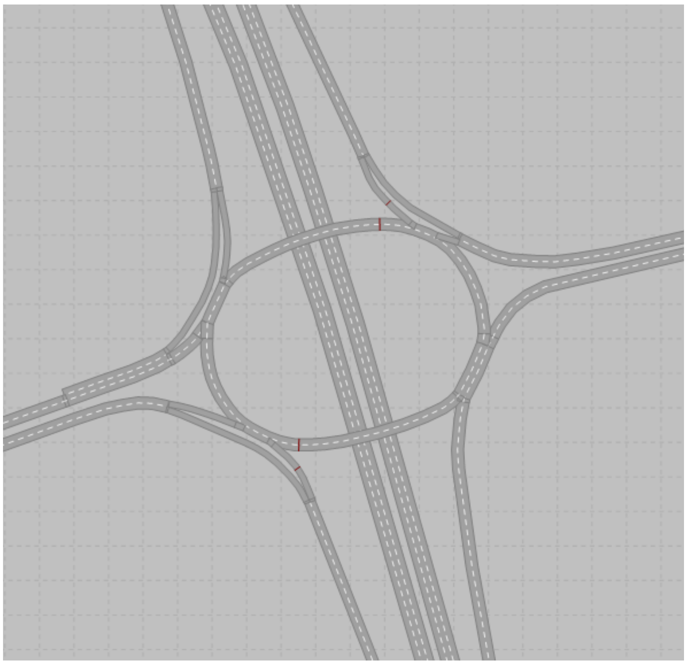
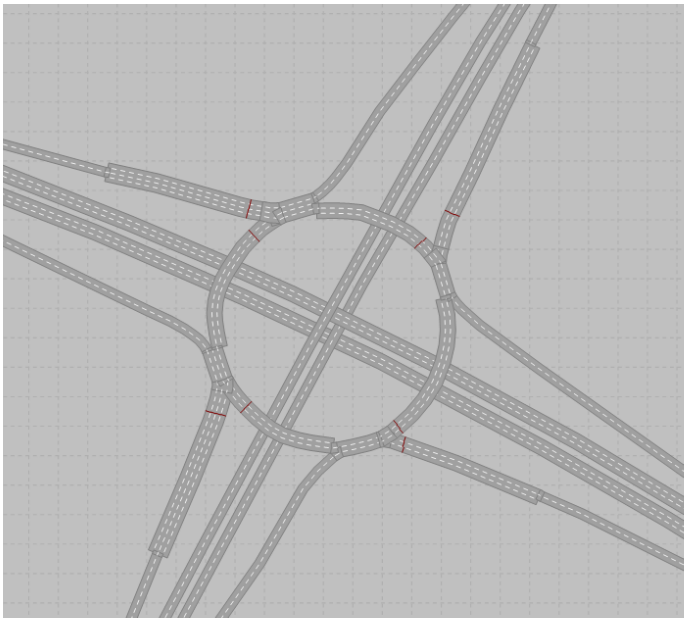


Figure 8: Fully signalised grade separated roundabout



4.1.2. Urban model (G)

Model G aims to capture the impacts of CAVs in urban city network. It consists of typical urban network elements such as signalised junctions, pedestrian crossings and public transport infrastructures as described in Table 5.

The model covers an approximate 3km stretch of urban A-road, including various side roads and intersections based on real-world network. The speed limit is therefore set to 30 mph. Although this model is not specific to a certain location, the network infrastructures and traffic signal timings are all built in line with TfL modelling guidelines to make sure the model is representative for the UK road network.

This model is approximately based on the A503 in North London. This corridor has been identified as providing an appropriate mix of junction types, PT infrastructure and lateral movement through lane changes and flares. An overview of the model is shown in Figure 9.

Figure 9: Overview of Model G, urban A-road

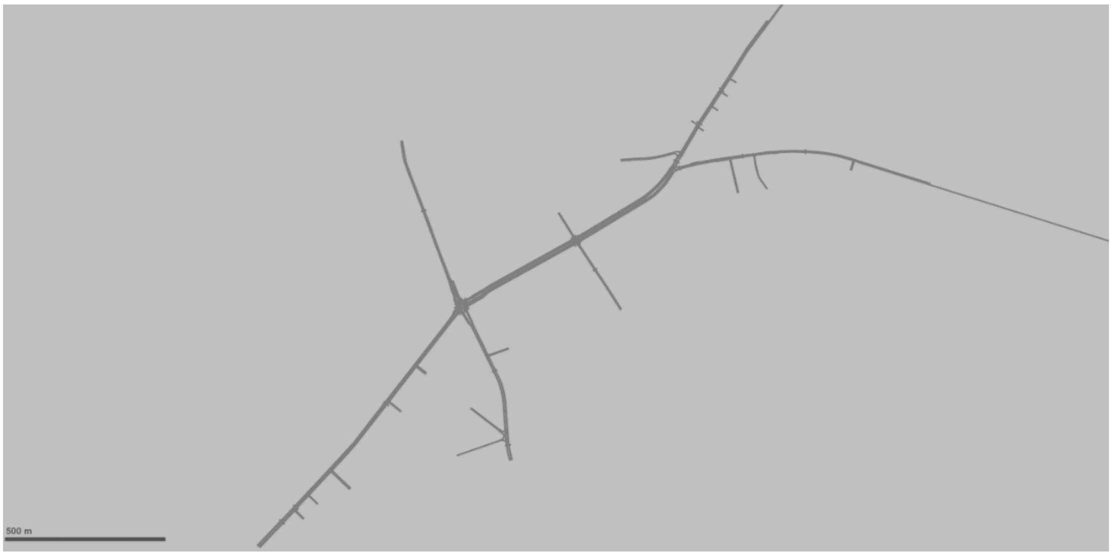
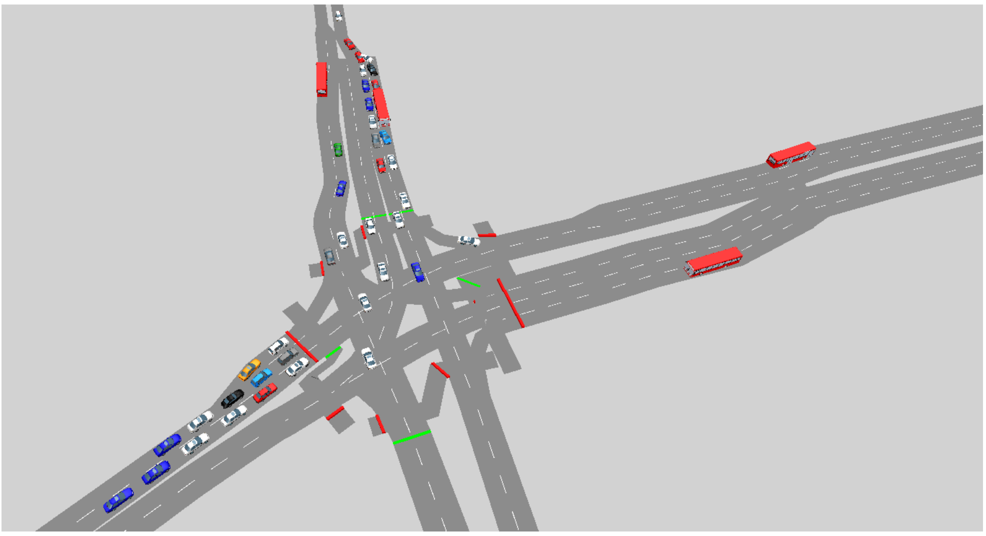


Figure 10 shows a detailed view of the central signalised intersection, showing various road geometries and stop line locations modelled. This includes pedestrian crossings and a dedicated bus lane.

Figure 10: Detailed view of signalised junction



Initial testing of these models was undertaken to ensure they are fit for purpose. This has ensured the base level of demand provides performance metrics associated with congestion and non-congested conditions, particularly in terms of average traffic speeds and queue lengths at junctions.

4.2. Capability

A variety of definitions exist for the capability of CAVs, including SAE International's levels of driving automation. This covers six levels (SAE 0 – 5), ranging from no automation to full automation. In other definitions, CAV capability is more broadly split into two categories, such as those used in the DfT's detailed regulatory review, "The Pathway to Driverless Cars".

These definitions are automotive specific, and will undoubtedly have significant impact on the experience of the driver and on the operation of individual, or indeed groups of, vehicles. However, they do not necessarily relate to fundamental changes to the behaviour of the vehicle-driver unit – such as the levers discussed in Chapter 3 of this report.

The approach taken has therefore been to define four levels of capability, specific to this modelling exercise, but relatable to various constructs used to describe connected and autonomous vehicle futures. Table 6 summarises these capabilities.

Table 6: Capability levels for modelling

Capability level	Name	Description
I	No automation	The base fleet of passenger cars and goods vehicles
II	Driver assistance	The driver remains in control, but vehicles are characterised as having better throttle control and smoother acceleration behaviour
III	Partial → high automation	The vehicle controls longitudinal and lateral behaviour as defined by the user
IV	Full automation	The vehicle controls longitudinal and lateral behaviour to an enhanced level

Level I (No automation) is used to describe the base fleet of passenger cars and goods vehicles. The default parameters are assumed with no parameter variation[18].

Level II (Driver assistance) employs parameters relating to speed oscillation and throttle control. The capability provided in Level II will also be applied to Level III and Level IV vehicles.

Level III (Partial → high automation) incorporates automated longitudinal and lateral behaviour. This level recognises the role of user choice, with some vehicles adopting assertive behaviour, and some adopting cautious behaviour.

Level IV (Full automation) replicates the behaviour of Level III, with a key difference. The DfT's detailed review, "The Pathway to Driverless Cars", describes a fully automated CAV as a vehicle in which the driver is not necessary. In this instance it is assumed that the driver has no input to the driving task, and as such the vehicle *will* move with enhanced longitudinal and lateral behaviour.

It is recognised that definitions of future states for CAVs cannot be easily or simply mapped to a microsimulation modelling environment. However, in constructing these levels of capability, the following things are noted:

- It is recognised that changes to vehicle capability will be incremental, with driver assistance and partial automation systems pervading initially;
- It is recognised that CAV penetration does not necessarily mean "enhanced" longitudinal and lateral behaviour with respect to traffic flow and road capacity – user choice will be a key determinant; and,
- It is recognised that a range of different CAV capabilities will be present in the vehicle fleet; as such, scenarios are developed that involve the four different capability levels deployed on the network simultaneously.

[18] It is recognised that some connectivity and automation exists in the existing vehicle fleet; however, in this case this simply represents the default parameter set

To represent the capability of CAVs in the microsimulation model, driving behaviour parameters will be modified for each capability level. Much of the functionality modelled in this work makes direct reference to autonomy of the vehicle. In many cases, connectivity of the driver-vehicle unit is necessary to make the autonomous functionality possible, and is therefore implicit in the model environment.

However, it is not possible to capture some expected CAV features within the traditional microsimulation environment. One such capability is to dynamically alter behaviour, as discussed in Section 3.2.2. In this case, logical rules have been defined where the type of following behaviour adopted is defined by the leading (rather than trailing) vehicle. These are shown in Table 7.

Table 7: CAV following behaviour rules

Following vehicle	Lead vehicle	Following behaviour
Legacy fleet	Any	Normal (legacy fleet) following behaviour
Assertive CAV	Legacy fleet	Normal (legacy fleet) following behaviour
Assertive CAV	CAV	Assertive following behaviour
Cautious CAV	Legacy fleet / Cautious CAV	Cautious following behaviour
Cautious CAV	Assertive CAV	Assertive following behaviour

Parameter variations implemented in the models are described in detail in Appendix B of this report.

4.3. Adoption and penetration

Whilst much has been written regarding the potential for CAV uptake and market penetration, no consensus has been reached. Given the embryonic nature of this industry, this is unsurprising. Studies have cited[19], in particular, concerns over cost to the consumer and changing models of car ownership and mobility provision.

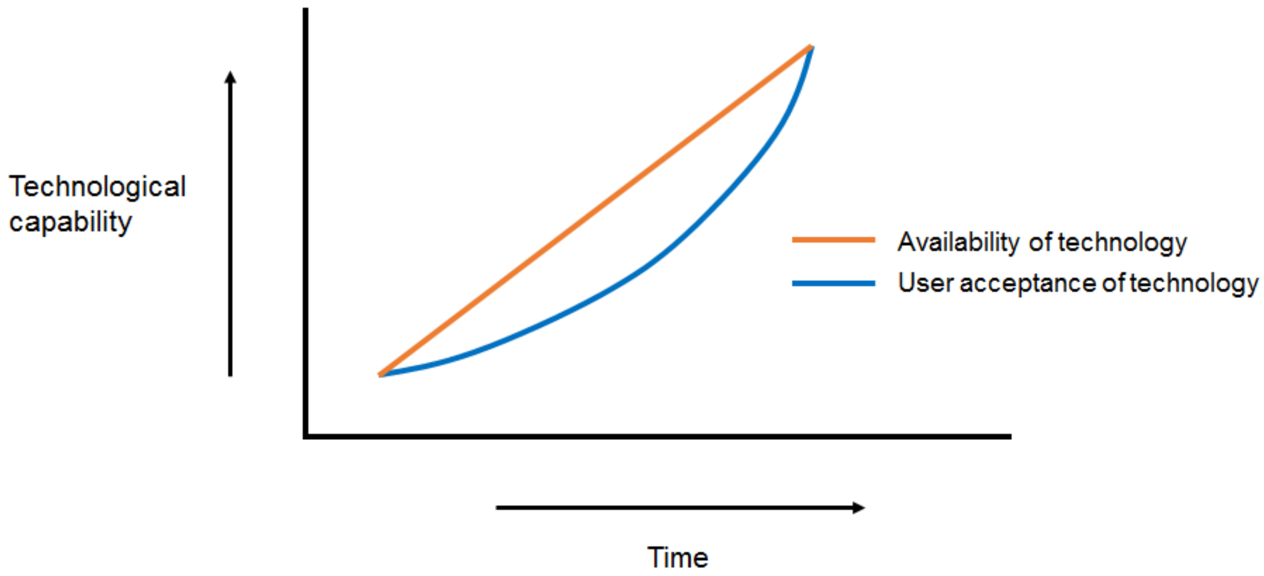
As the aim of this work is to investigate potential impacts of CAVs on road network performance, a straightforward approach to CAV capability and fleet penetration has been taken. This is based upon some basic principles that are widely accepted:

- At low market penetration, technical capability will be limited (for example, to driver assistance and low levels of autonomy); and,
- As market penetration increases, consumer confidence will also increase and better use of connected and automated technology will prevail.

Figure 11 shows an example projection for the increasing technical capability of CAVs over time. In this case, the availability of the technology is not aligned with the user acceptance of technology. These trends do converge – perhaps representing the future fully autonomous state considered in many previous studies – but in the short term, availability of technology does not necessarily lead to wide scale deployment.

[19] Litman, T., 2014. Autonomous Vehicle Implementation Predictions. *Victoria Transport Policy Institute*, *28*.

Figure 11: Future states of availability and user acceptance



Technological change is usually marked by early adopters prior to full saturation. The scenarios for CAV deployment should reflect this.

4.4. Modelling scenarios

The modelled scenarios are summarised in Table 8. The proportion of CAVs in the vehicle fleet increases with successive scenarios. Within the CAV fleet, the capability of vehicles also changes, representing elements of user choice and confidence in technology.

Table 8: Fleet penetration scenarios

Scenario	Legacy fleet *Level I*	CAV penetration *Level II – IV*	*CAV penetration composition*					
			Level II	*Level III – Cautious*	*Level III – Normal → Cautious*	*Level III – Normal → Assertive*	*Level III – Assertive*	*Level IV*
Base	100%	0%	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
25% penetration (1)	75%	25%	*20%*	*1.25%*	*1.25%*	*1.25%*	*1.25%*	*0%*
50% penetration (2)	50%	50%	*35%*	*2.5%*	*2.5%*	*2.5%*	*2.5%*	*5%*
75% penetration (3)	25%	75%	*50%*	*3.75%*	*3.75%*	*3.75%*	*3.75%*	*10%*
100% penetration (4)	0%	100%	*40%*	*10%*	*10%*	*10%*	*10%*	*20%*
Upper bound (5)	0%	100%	*0%*	*0%*	*0%*	*0%*	*0%*	*100%*

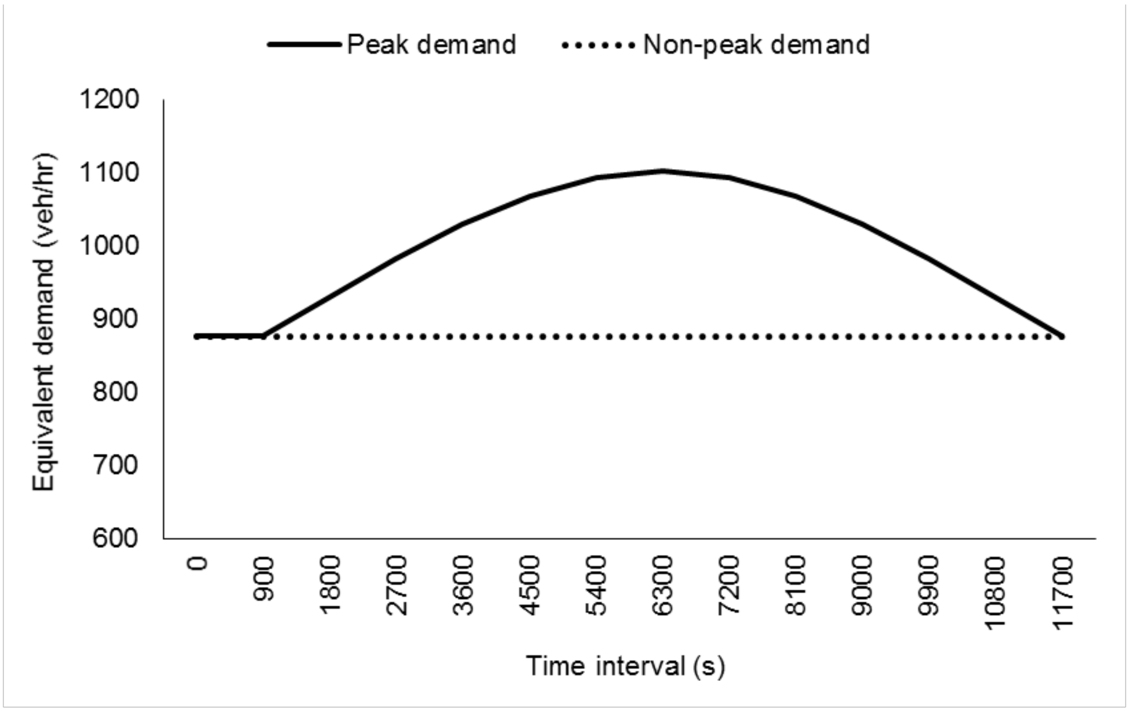
The fifth scenario represents an upper bound, where 100% of the fleet is "fully autonomous".

Two separate demand situations are considered:

- A "peak" period model, in which the base is characterised by congestion, queuing, delays and low traffic speeds.
- A "non-peak" period model, where vehicle speeds close to free-flow are maintained.

The peak period in each model is subject to varying levels of demand, reflective of that observed in the AM peak generally. An example shown Figure 12.

Figure 12: Demand profile



To reflect the inherent uncertainty associated with traffic, 10 random seeds will be used for each scenario, giving a range of results.

5. Simulation results

5.1. Overview

Five scenarios, with different levels of CAV market penetration, were implemented in each base model. These were conducted for congested, “peak” demand periods and uncongested, “non-peak” demand periods. Taking into account 10 random seeds and the base (“do-nothing”) situation results in more than 200 simulation model runs.

The results for each model focuses on three main aspects:

- Network performance, which looks at the overall performance of the whole network, including average vehicle delay and average vehicle speed;
- Junction performance, which looks at the delay of vehicles going through the specific junctions in the network ; and
- Travel time, which looks at the average journey time of vehicles on defined travel time segments.

Where data is presented graphically, lines of best-fit are used to aid with interpretation. Whilst representative, these do not necessarily relate to a particular form of relationship. A full set of results is included in the *Stage 2 Technical Report*.

Given the complex nature of the networks, and the realistic demand situation evaluated, it is not practical to provide a measure of “capacity”. Capacity has been evaluated in isolated situations, described as “simple models”, and detailed in full in the *Stage 2 Technical Report*.

The remainder of this section presents some high level results for the two models. Results tables are also included in Appendix C. Table 9 shows results for the SRN model with peak demand. The percentage values show the difference relative to the base

Table 9: Summary results – SRN model, peak period

Scenario	Average delay (s)		Average journey time (s)		Journey time variability[20] (s)		Coefficient of variation[21]	
	(s)	%	(s)	%	(s)	%		%
Base	35.84	-	539.79	-	20.17	-	0.0374	-
(1) 25% CAV	36.17	*+0.9%*	538.49	*-0.2%*	19.38	*-3.9%*	0.0360	*-3.7%*
(2) 50% CAV	33.39	*-6.8%*	533.62	*-1.1%*	17.65	*-12.5%*	0.0331	*-11.5%*
(3) 75% CAV	29.77	*-16.9%*	527.72	*-2.2%*	15.33	*-24.0%*	0.0291	*-22.3%*
(4) 100% CAV	23.72	*-33.8%*	517.77	*-4.1%*	10.52	*-47.9%*	0.0203	*-45.7%*
(5) Upper bound	21.38	*-40.3%*	479.29	*-11.2%*	9.14	*-54.7%*	0.0191	*-49.0%*

The low CAV penetration case (25%) results in only minor benefits to journey time[22], and small disbenefits to average delay. The small amount (5%) of CAVs are either cautious, or limited in their ability to be assertive by

[20] Defined as the standard deviation

[21] Defined as the ratio of the standard deviation to the mean

[22] Journey time segment JTa, see Section 5.2.3 for more details

the existing vehicle fleet. The benefits here are likely to be from improved decision making and better throttle control.

At 50% penetration of CAVs, there is an approximate 7% improvement in delay, 1% improvements to average journey time, and an 11% improvement to the variability of journey times[23]. Benefits to all metrics increase to the upper bound, which represents 100% penetration of fully automated CAVs which demonstrate “assertive” behaviour (characterised as close following behaviour and low gap acceptance thresholds).

Journey time benefits appear to be far outweighed by the reduction in the *variability* of journey times. For example, at 100% penetration of CAVs (Scenario 4), reductions in journey times are a little over 4%, yet variability is reduced by around 50%.

This, coupled with the reduction in delay, suggests wide scale CAV deployment on the strategic road network could result in smooth traffic, better resilience and an improved user experience.

Table 10 shows summary results for the urban model. When compared to the SRN model, this simulation yields more significant results for a small (25%) penetration of CAVs. The percentage values show the difference relative to the base

Table 10: Summary results – urban model, peak period

Scenario	Average delay (s)		Average journey time (s)		Journey time variability (s)		Coefficient of variation	
	(s)	%	(s)	%	(s)	%		%
Base	65.91	-	277.78	-	88.38	-	0.3182	-
(1) 25% CAV	57.70	*-12.4%*	219.52	*-21.0%*	19.74	*-77.7%*	0.0899	*-71.7%*
(2) 50% CAV	54.44	*-17.4%*	205.35	*-26.1%*	10.01	*-88.7%*	0.0488	*-84.7%*
(3) 75% CAV	51.89	*-21.3%*	198.72	*-28.5%*	7.24	*-91.8%*	0.0364	*-88.6%*
(4) 100% CAV	48.02	*-27.1%*	192.64	*-30.7%*	6.00	*-93.2%*	0.0312	*-90.2%*
(5) Upper bound	46.36	*-29.7%*	184.25	*-33.7%*	5.71	*-93.5%*	0.0310	*-90.3%*

Whilst there are continuing improvements to network performance with successive CAV scenarios, this initial progress is most striking.

On high speed sections of the strategic road network, a key source of benefits will be in vehicles travelling at reduced longitudinal spacing whilst maintain speed, in effect increasing operational capacity of the carriageway. Due to the high number of conflicting movements and mix of different users (motorised and non-motorised), urban areas are generally subject to much lower speed limits. As such, the benefits from high-speed, high-density traffic are unlikely to be realised.

However, the better throttle control expected from driver assistance technologies in the short term may result in particular benefits in urban areas, with smoother traffic flow and better maintenance of vehicle speeds.

[23] Taken as the coefficient of variation

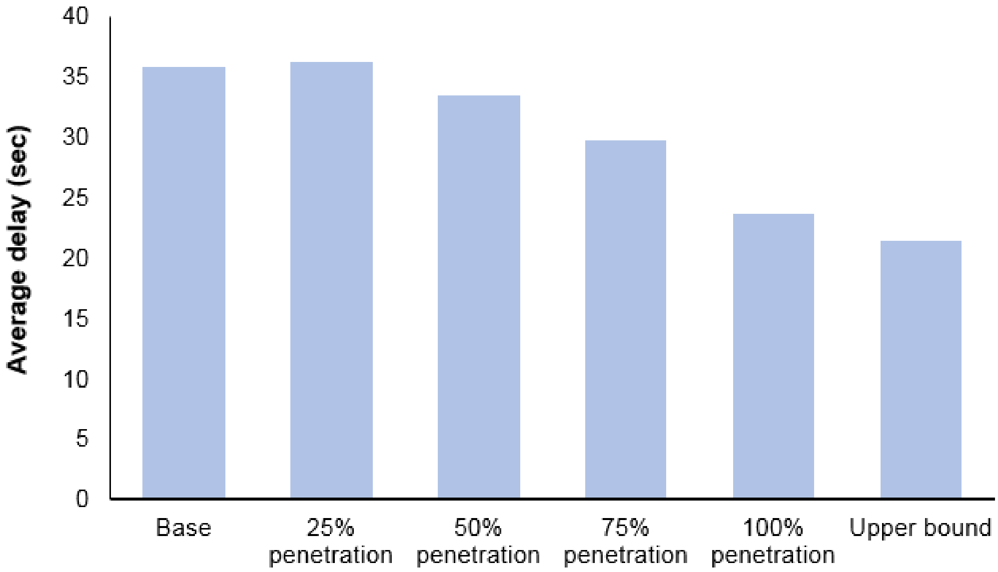
5.2. Strategic highway network model detailed results

The SRN model (F) examines the strategic road network as typical to the UK, including high speed sections, free-flow interchanges and grade-separated signalised junctions.

5.2.1. Network performance

Increasing penetration of CAVs can result in a decrease in average delay on the network (Figure 13). The upper bound of fully automated CAVs results in a 40% improvement in delay.

Figure 13: SRN model network delay (peak period)



However, with a low penetration of CAVs, some of which will adopt cautious behaviour, total delay can be seen to marginally worsen. Whilst not a large difference, the major conclusion is that a low penetration of low capability CAVs may not result in an improvement to network performance.

A low penetration of low capability CAVs is unlikely to contribute positively to measures of network performance

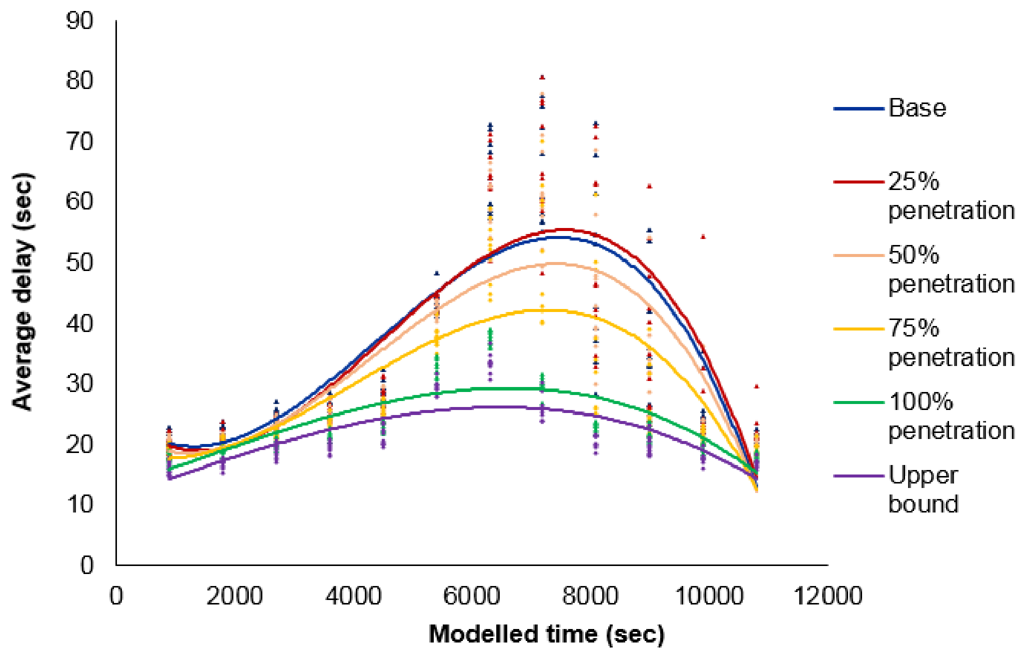
Figure 14 shows the progression of delay throughout the modelled time period, with around 3 hours shown in total (i.e. following the profile shown in figure 12). As demand builds up, the base and low penetration scenarios experience increasing congestion and delay. The curves converge once again as demand drops and congestion is reduced.

Neither the 25% nor 50% penetration scenarios offer much benefit over the base case. The reasons for this are thought to be two-fold:

- A small deployment of cautious CAVs (more cautious than the base vehicle fleet) induce additional delay; and,
- The behaviour of the assertive CAVs is limited by the overwhelming number of non-CAV vehicles (i.e. they are unable to follow at shorter time gaps in the majority of following situations).

This is an important point; if the level of behaviour adopted CAVs is variable according to the situation, a “critical mass” of CAVs may be required to see benefits on a network level. In this scenario, significant benefits are only evident at 75% penetration of CAVs (approximately 17% for network delay).

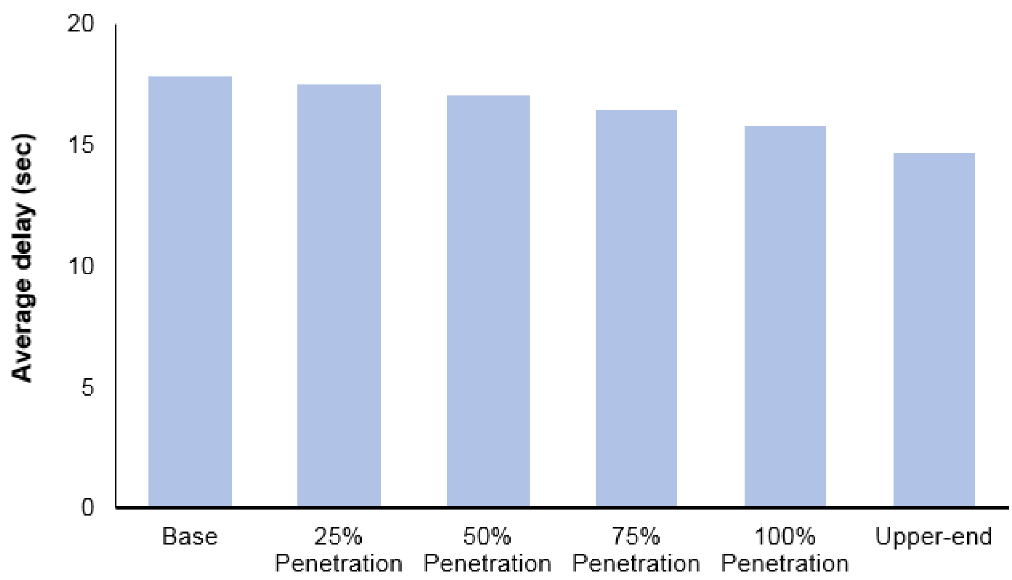
Figure 14: Network delay by simulation time (peak period)



> ***At low penetration, the benefits of CAVs are likely to be constrained by the limitations of the existing vehicle fleet***

As expected, congestion and delay benefits are much lower (<10%) in non-peak periods (Figure 15). This confirms that the major network benefits of CAVs are likely in periods with high demand where congestion is prevalent.

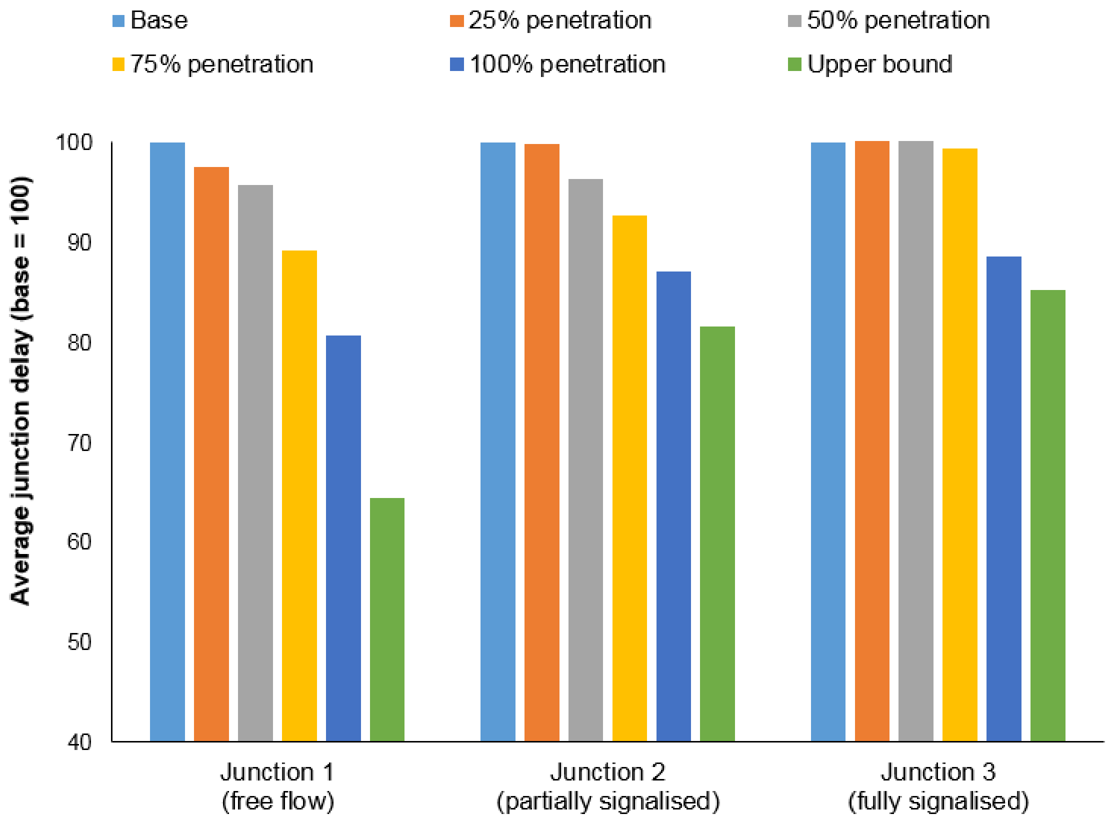
Figure 15: SRN model network delay (non-peak period)



5.2.2. Junction performance

The performance of three junctions were considered individually. These are a free-flow interchange (previously shown in Figure 6), a partially signalised grade-separated roundabout (Figure 7) and a fully signalised grade-separated roundabout (Figure 8). Figure 16 shows the performance of each in terms of delay when compared to the base situation.

Figure 16: Model F average junction delay (peak period)



The most significant improvements are seen at the free-flow interchange, with a reduction in delay of as much as 35%. This is likely the situation where the improvements offered by assertive CAVs – high-speed, high-density traffic – can be best realised.

Free-flow interchanges will benefit through maintaining high-speed, high-density traffic flows

Less benefit is seen at the signalised junction sites, but improvement in delays of up to 20% can still be expected. Cautious CAVs and the legacy fleet are likely to cause a greater impedance to assertive CAVs in this example, with the clearance of queues more difficult.

It should also be noted that as traffic signal timings have not been changed in future situations, they are unlikely to be optimal for changing traffic characteristics.

5.2.3. Travel time

Particular routes have been considered to assess the impact on journey times, as shown in Figure 17. Comprehensive results for modelled journey time are shown in Appendix D.

Figure 17: SRN model journey time segments

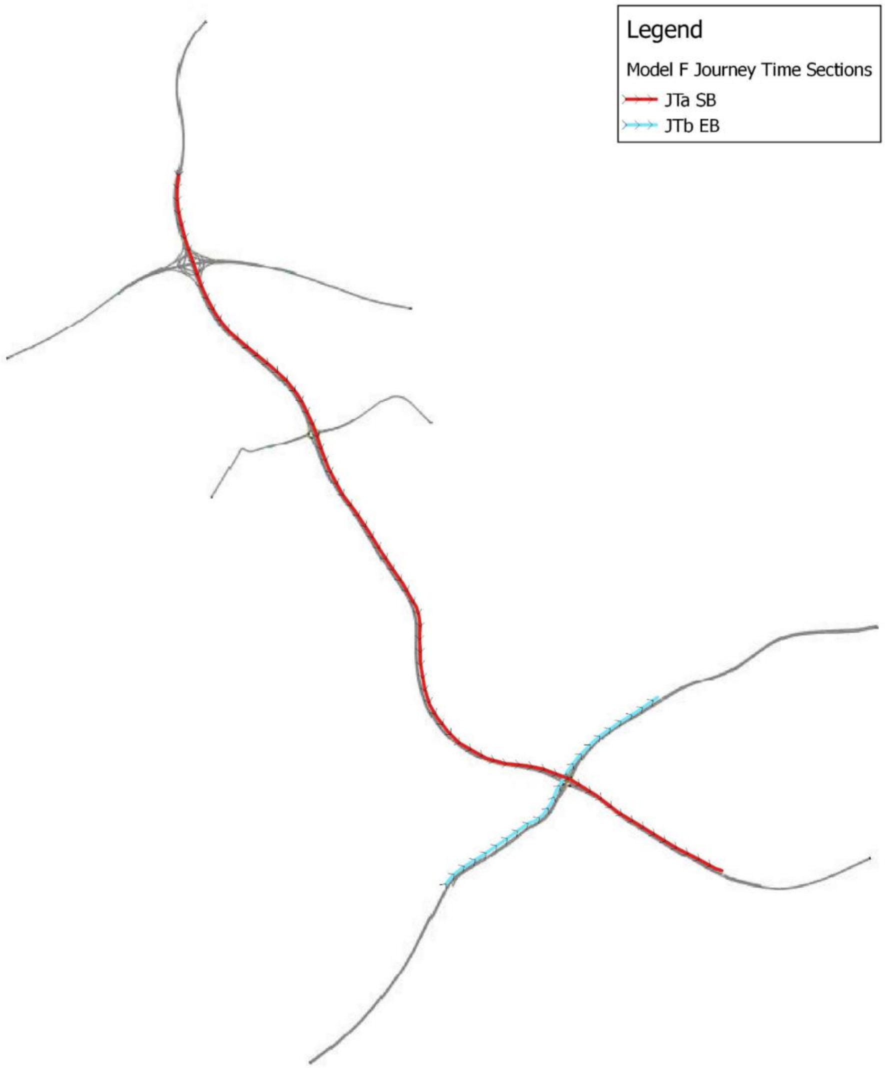
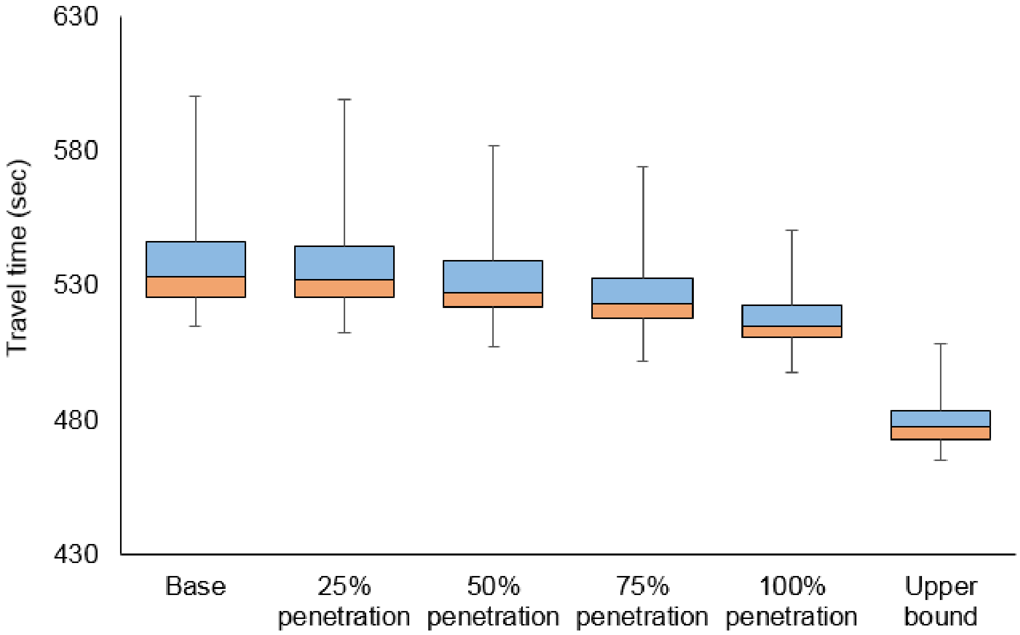


Figure 18 shows the range of modelled journey times as a series of box-and-whisker plots. There is a clear improvement in journey times with increasing penetration of CAVs.

Figure 18: SRN model journey times (segment JTa) peak period



Again, significant improvements are only seen at higher (>75%) penetrations. Alongside the average (in this case, the median) journey time decreasing, the range also becomes smaller. This implies an improvement in the reliability of journey times with increasing deployment and capability of CAVs.

This can be displayed as the variability in journey time (the standard deviation or coefficient of variation as shown in Table 9). Depending on the characteristics of the connected and autonomous vehicles, improvements of around 45-50% can be expected in a 100% penetration scenario.

High penetration of highly capable CAVs could lead to improvements in the reliability of journey times of around 50%

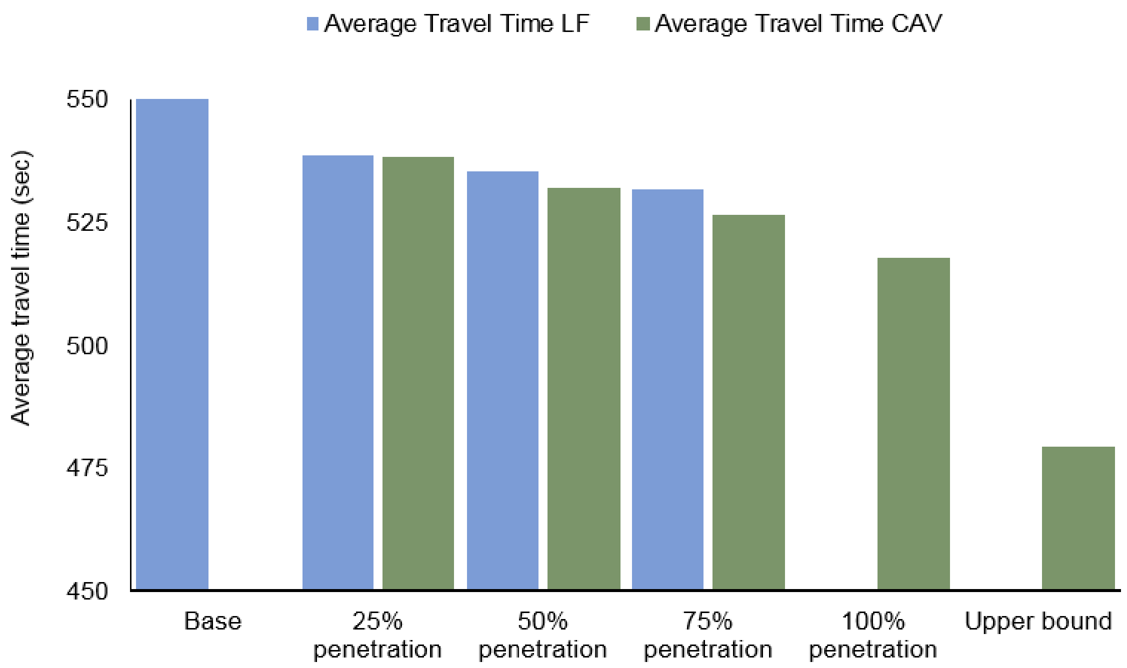
The exception to this is, again, the 25% penetration case. In this instance, the modelled vehicle fleet has become more heterogeneous *and* less capable, resulting in a wide range of modelled journey times, and a slight decrease in average journey time and journey time variability.

Figure 19 shows the average journey time for the connected and autonomous vehicle fleet (CAV), and the existing, legacy, vehicle fleet (LF). Both sections of the vehicle fleet benefit from the improvements, suggesting that benefits are available to users and on a network level.

Improvements offered by CAVs could potentially provide journey time benefits of more than 10% to all motorists in peak times

Full results relating to journey times are included in Appendix D of this report, and in the *Stage 2 Technical Report.*

Figure 19: Average (mean) SRN model journey times (segment JTa) peak period



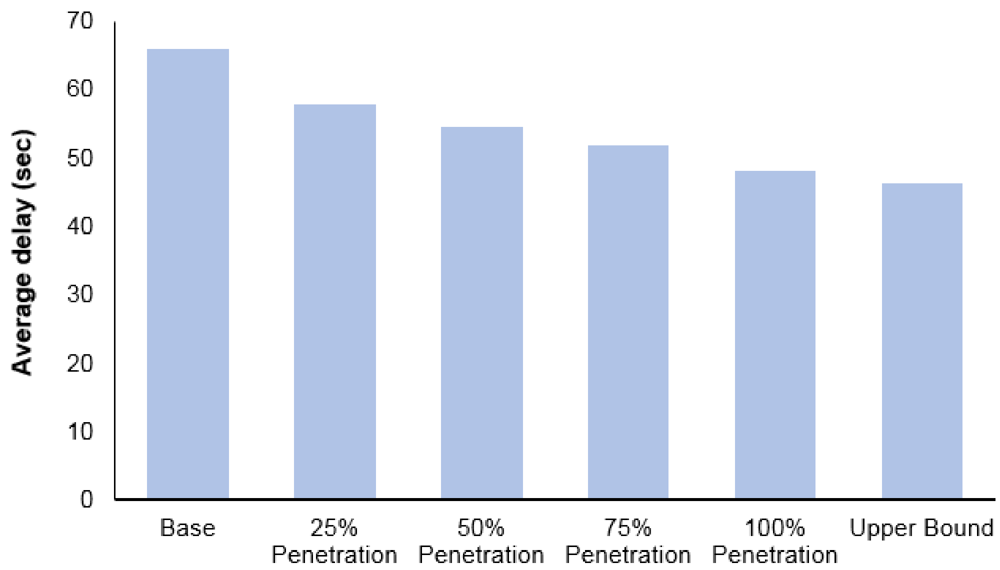
5.3. Urban road network model detailed results

The urban model (G) examines an urban A road as typical to the UK. This includes signalised junctions, pedestrian crossings and dedicated public transport infrastructure.

5.3.1. Network performance

The urban model shows successive improvements in performance with increasing CAV capability (Figure 20).

Figure 20: Urban model network delay (peak period)



This is a different picture to that seen in the high-speed SRN model; benefits are gained at low-penetration, with relatively low-capabiliy CAVs. The reason for this is rooted in the different types of vehicle behaviour in each situation.

The major improvement to the vehicle fleet at low CAV penetrations has been referred to as “driver assistance”. In this modelling exercise, this has been characterised by greater throttle control (meaning better maintenance of speed). This helps in harmonising traffic flow, cutting out a substantial proportion of speed variation which leads to congestions – in essence, smoothing traffic flow.

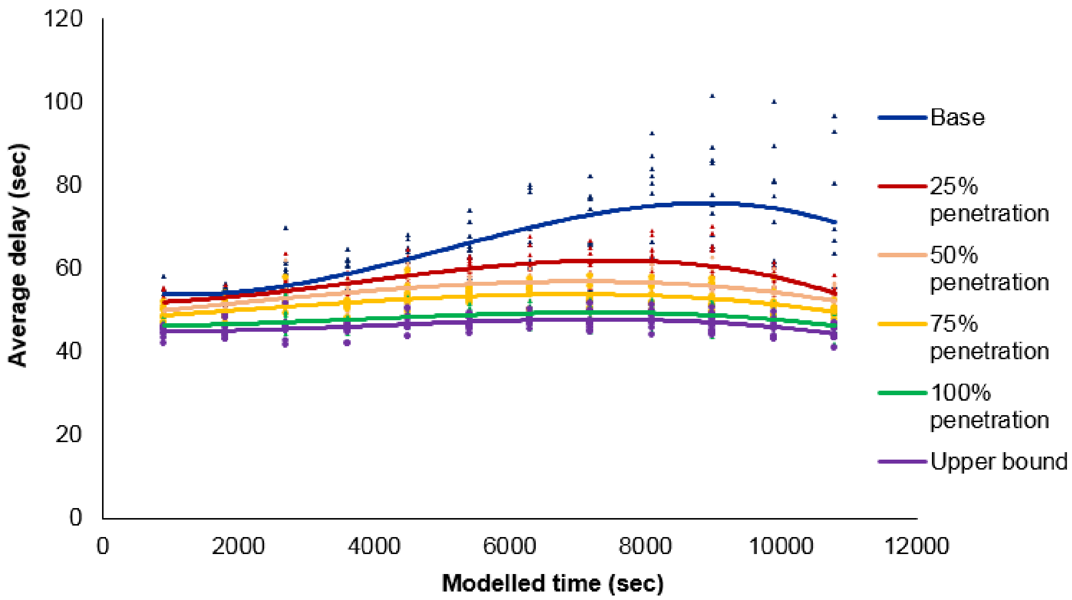
Urban areas, with low-speed, stop-start traffic may benefit most from relatively low-tech “driver assistance” helping to maintain flow

Simulation results (Table 10) suggest a reduction in journey time variability by as much as 80% with a 25% deployment of CAVs. It is likely that this results in a “tipping point”, where the improvements in vehicle dynamics enables an otherwise saturated network to function. Whilst benefits of this scale may not be experienced in all situations, the potential for improvement is evident. This is supported by results for the non-peak period[24], where a 25% deployment in CAVs results in a near 30% improvement in journey time variability.

As the proportion of CAVs increases, a greater proportion of the vehicle fleet is enabled with this technology. However, as speeds are necessarily limited to a greater extent in urban areas, benefits seen on the SRN, relating to closely spaced highly automated vehicles at high speeds, are not observed.

This is supported by the progression of delay through the modelled time period (approximately 3 hours in total), as shown in Figure 21. There are immediate improvements to congestion with a small penetration of CAVs, and faster recovery of the network.

Figure 21: Urban model network delay by simulation time (peak period)



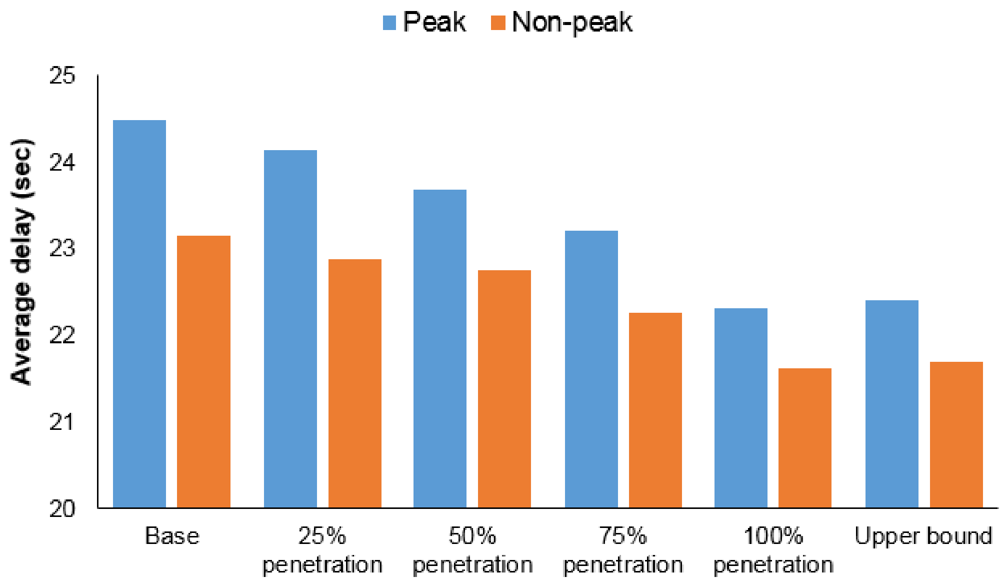
5.3.2. Junction performance

At the centre of the urban model is a signalised junction. This is a fairly typical situation in the UK, with conflicting traffic streams and pedestrian facilities. Figure 22 shows the improvements in junction delay with increasing CAV penetration. As expected, benefits are greater in the lower-demand (non-peak) situation.

[24] Summary results tables are included in Appendix C

In this case, the upper bound (100% penetration of fully automated vehicles) does not represent the best case, with slightly higher delay than 100% mixed-CAV penetration. Whilst the difference is unlikely to be statistically significant, it is also worth considering that the timings of the signalised junction are not optimised for the future state.

Figure 22: Urban model signalised junction delay



5.3.3. Travel time

Journey times have been considered for the most congested route, as shown in Figure 23.

Figure 23: Urban model journey time route

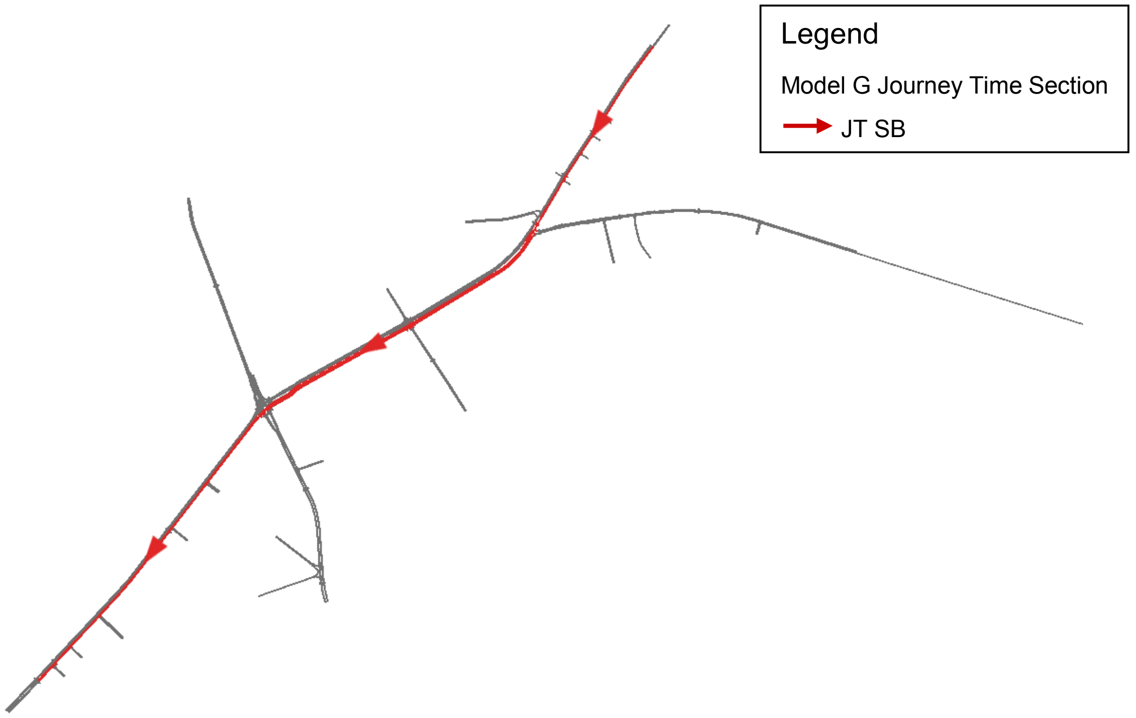
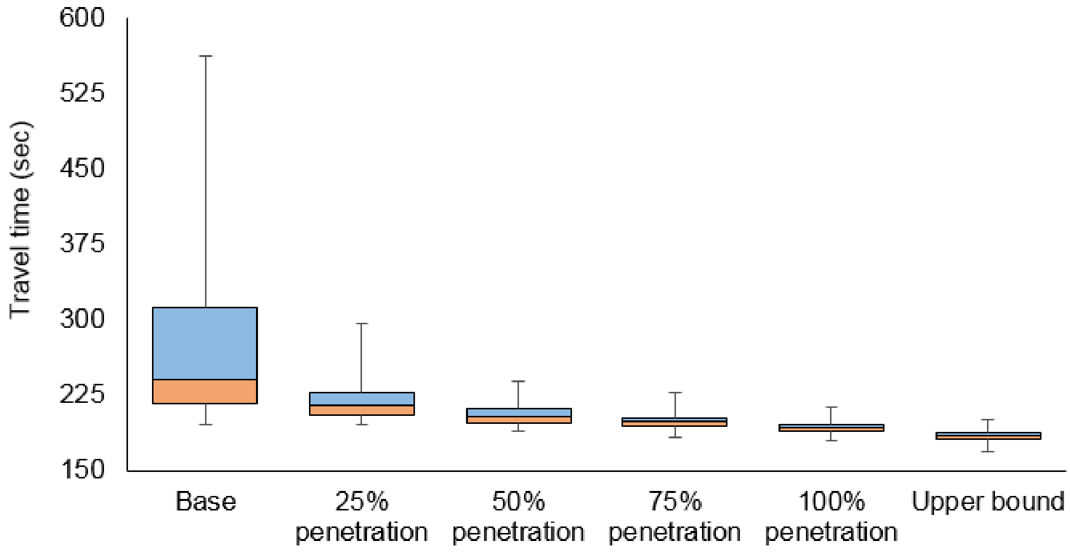


Figure 24 shows the distribution of travel times in the form of a box-and-whisker plot. The introduction CAVs has substantial benefit, particularly to the range of journey times.

Figure 24: Urban model journey times (peak period)



Improved throttle control and consistency of speed may be beneficial to journey time reliability in urban areas, even at low penetration

Figure 25 shows this trend for a constrained range of data. The improvements are evident, both in average journey time and in the range, representing network operations and reliability.

Figure 25: Urban model journey times, constrained view (peak period)

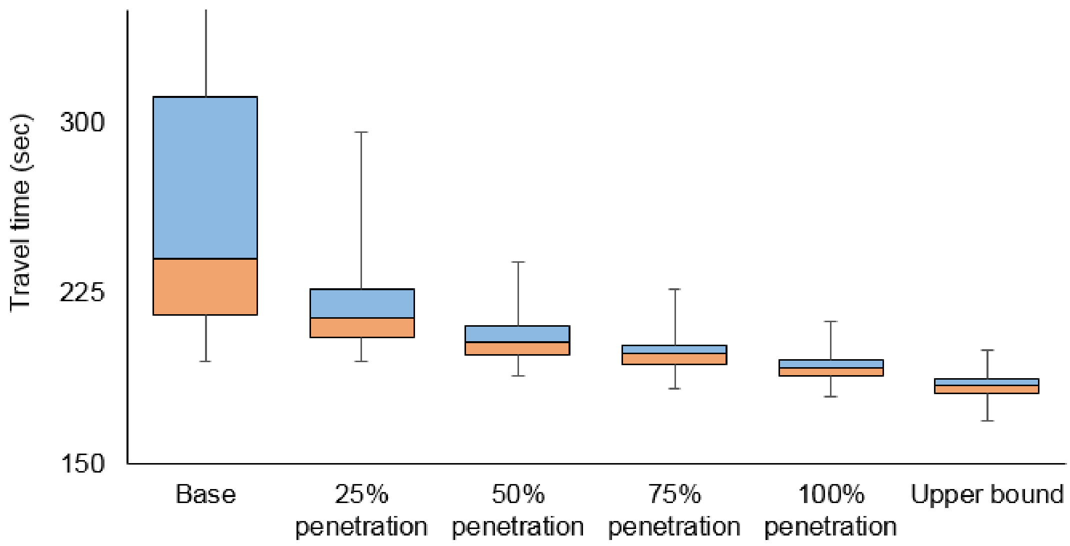
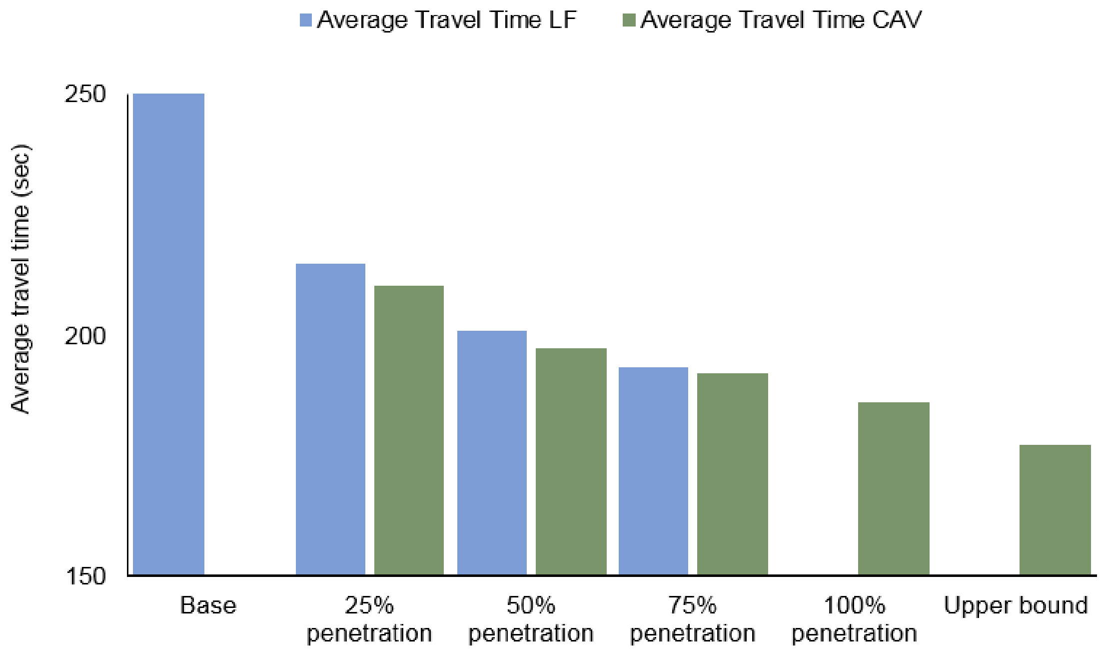


Figure 26: Urban model journey time (peak period)



As with the SRN model, benefits are gained from the entire vehicle fleet, whether connected and autonomous or not. A comprehensive summary of modelled journey times is shown in Appendix C of this report.

6. Conclusions and recommendations

This chapter draws together the conclusions of this work, highlights some specific questions and knowledge gaps that remain, and finally make recommendations for further work in this field.

6.1. Potential impacts on traffic flow and network performance

The mechanisms by which connected and autonomous vehicles could impact traffic flow, network performance and road capacity are, in the main, reasonably well understood and broadly accepted. This study has explored the impact of potential behavioural changes relating to:

- Changed longitudinal movement of vehicles;
- The ability to change following behaviour based on the capability of the lead vehicle;
- Different levels of gap acceptance and lane changing behaviour; and
- Connectivity to represent better provision of inform decision making.

The major conclusions of this work are detailed below. These conclusions must be considered in the context of the underlying assumptions around CAV penetration and, crucially, capability.

The potential for reductions in network performance, rather than improvements

A review of literature highlighted the importance of user choice – it should not be assumed that CAVs will offer enhanced behaviour over the existing vehicle fleet. Accounting for user preference, comfort and safety, it is *plausible* that at least a section of the emerging CAV vehicle fleet is more cautious than that currently operating. This has been represented in the design of CAV scenarios, with early (low penetration) deployments of CAVs including a relatively high proportion of cautious vehicles. This results in a **potential decrease in effective capacity and a decline in network performance**, especially in high-speed, high-flow situations (such as the SRN). This is also demonstrated for isolated road network situations, detailed in the *Stage 2 Technical Report*.

Substantial benefits may not be achieved until high levels of connectivity and automation

There is great potential for substantial improvements in network performance, particularly in high-speed, high-flow situations. However, there is evidence that at low penetrations, any assertive CAVs are limited by the behaviour of other vehicles; that vehicles are not able to make use of their enhanced capability. This leads to suggestion of a tipping point – the proportion of enhanced vehicles required before benefits are seen. This work suggests this may be between 50% and 75% penetration of CAVs. Results for the SRN (peak period) indicate improvements in delay of only 7% for a 50% penetration of CAVs, increasing to 17% for 75% penetration and as high as 40% for a fully automated vehicle fleet.

Benefits to congested networks

Benefits are much greater in congested networks, illustrated by the “peak” demand scenario. This is expected, as changing vehicle behaviour allows higher density traffic. As uncongested networks are not constrained by traffic density, improvements are not seen. Some improvements are evident in uncongested networks, illustrated by the “non-peak” demand scenario. This may be associated with areas of the network that act as “bottlenecks”, such as junctions, as the greater throughput of traffic will still yield user benefits. However, this does not have great benefit to network-level measures of performance.

Low speed urban areas may benefit most from low-tech driver assistance capability

The benefits to the SRN, where high-flow and high-speed situations prevail, are when vehicles can travel more closely spaced and maintain speed at a very high level of flow. Due to the traffic mix of motorised and non-motorised users, urban areas necessarily have lower speed limits. There is therefore a lower limit to what can be achieved through more closely spaced vehicles.

Low capability (and more immediate) CAVs are termed to have “driver assistance” technologies. In this exercise, this has been characterised by better control of speed. This helps to maintain the spacing of vehicles and reduces unnecessary acceleration and decelerating operations. Results from the urban model suggest initial benefits to delay of more than 12% with a 25% penetration of CAVs, rising to 30% with a fully automated vehicle fleet.

Reliability is likely to improve

The major measures of network performance – such as journey time and delay – have been shown to generally improve with increasing penetration and capability of CAVs. However, there is also evidence that reliability will also improve[25]. Furthermore the scale of improvement in reliability far outweighs that shown in general performance – in the urban model in particular, benefits of between 30% and 80% are shown with a 25% penetration of CAVs, dependent on the demand situation.

Benefits are not constrained to one class of user

The increased capability of a subset of the fleet does not limit benefits to just those vehicles. Benefits are apparent for both CAVs and the unchanged legacy fleet, demonstrating that improvements can be expected for all network users.

There is inherent uncertainty associated with this work. Whilst grounded in literature review, it has been necessary to make a series of assumptions regarding the future penetration and capability of CAVs. This raises a series of key questions for policy makers, regarding **the capability available in CAVs** and the **penetration and uptake of CAVs**.

Without intervention, capability will be tailored by automotive manufactures to the demands of the user. As the automotive industry is not charged with the safe and efficient operation of the road network, maximum benefits to the network may not be obtained. A key question for policy is therefore how best can CAVs provide network-wide benefit, relating to their capability, penetration and uptake.

6.2. Recommendations for further work

As an emerging area of interest, there is clearly scope for substantial further work. This is particularly true in the area of transport planning and network operations, where increased knowledge of the capability of CAVs allows for a more detailed assessment of their potential impacts. These recommendations consider four broad areas:

- Addressing the limitations of modelling vehicle behaviour;
- Evaluating the impact on safety and driver error
- Modelling the impact on emissions and the environment; and,
- Considering how CAVs may change the fundamental drivers of travel demand.

6.2.1. Modelling limitations

Microsimulation modelling is a useful tool to inform appraisal and engineering design. However, there are limitations in the approach which require further thought when evaluating a change to the base vehicle fleet.

Representing vehicle behaviour

Microsimulation is less often used for variation of the characteristics of the underlying vehicle fleet. In general, it is preferable to validate the current (base) situation according to the parameters of interest – such as journey time and traffic flow. In this case, the base parameters of interest are related to the fundamental operation of the vehicle, including, but not limited to:

- Acceleration behaviour;
- Variation (oscillation) in speed;
- Gap acceptance; and,
- Distribution of vehicle headways.

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[25] Considered as either the standard deviation or coefficient of variation of journey time

As these are not characteristics generally measured, particularly on a network-level, it is generally assumed that microsimulation recreates this behaviour well for the modelled situation. Where CAVs are influencing these elements of vehicle operation, it is important to question how well we understand the current situation – the base case – and to qualify any conclusions drawn with this knowledge. This should be an important pillar of further work.

Interactions in increasingly complex situations

Over time, as technology improves, connected and autonomous vehicles are likely to be deployed in increasingly complex environments. It is therefore important to understand not just the interaction between CAVs and other vehicles, but the interaction with cyclists, pedestrians and other non-motorised users.

Further to this, better modelling tools may be required to account for these interactions and test the "system" effects of fundamental changes to vehicle operations, such as the introduction of connectivity and autonomy.

Limited situations

This work has considered two specific situations, the SRN and an urban road network, with typical levels of demand. Furthermore, isolated situations common to the UK road network have been examined as part of a series of simple models[26].

Whilst this is a practical approach to inform policy, specific results relating to improvements in demand, journey time and capacity must be considered appropriate to the situations being modelled. The major contribution of this work is not in providing exact estimates of improvements to network performance, but in demonstrating the important mechanisms of action, and the potential benefits and constraints of step-changes in vehicle capabilities. Quantitative analysis such as this should therefore be re-visited as more information regarding emerging vehicle technologies becomes available.

6.2.2. Safety and driver error

Safety is a key driver of the development of CAV, a key consideration for regulations and a potential source of benefits. Microsimulation modelling does not generally include the facility to consider safety and driver error, and so they have not been part of this work.

Driver error

Traffic analysis and microsimulation generally considers an "average" type of driver behaviour in modelling vehicle dynamics. In reality, theoretical road capacity is not achieved due to heterogeneity in driver behaviour and the potential for error. For example, the maximum attainable throughput during green time at traffic lights is not possible if the lead driver hesitates, resulting in "lost time".

In order to quantify this benefit, the scale of this problem needs to be better understood, allowing a proportion of network delay to be attributed to driver hesitation and error.

Safety

The benefits for safety can be considered at both the network and operational level, through traffic modelling and other analysis.

Network-wide, increasing penetrations of CAVs are likely to influence both the **severity** and **rate** of incidents and accidents on the road network. By incorporating understanding of this, and on the current impact of such incidents on network performance[27], the potential for improvements of varying levels of CAV penetration can be evaluated. This work is dependent on understanding the likely change in **risk** of a deployment of different connected and autonomous vehicle technologies.

[26] Discussed in detail as part of the Stage 2 Technical Report
[27] From, for example, Highways England data sources

Operationally, there is scope for testing of CAV control methods in terms of **response to incidents**. For example, the response of CAVs to dynamic lane closures and openings on the strategic road network would likely have an impact on link and junction performance, particularly at high penetration.

6.2.3. The impact on emissions and air quality

Improved network performance is likely to yield some environmental benefits. However, as we are considering a future state, there is also the need to account for potential improvements in emission control technologies, and fleet penetration of electric and other low-emission vehicles.

Traffic and environmental modelling can be used to evaluate the potential for changes in vehicle power demand, exhaust emissions, air quality and even human exposure to pollution. This should not be considered in isolation, as changing models of car ownership and travel demand may induce additional trips or incite mode shift.

This should be considered as part of a more complex modelling exercise, accounting for a number of potential future scenarios. In particular, it is recommended that this work accounts for projections to vehicle fleet changes concerning alternate powertrain technologies (for example, the penetration of electric and hybrid vehicles).

6.2.4. The fundamental drivers of travel demand

The ultimate state of vehicle fleet consisting solely of connected and automated vehicles is likely to fundamentally change the drivers of travel demand.

On the most basic level, improvements to network may decrease the generalised cost of travel, and therefore potentially generate additional trips, with further adverse effects. This work has not explored traveller's response to this cost. However, there are added complexities to consider, such as:

- The benefits to the user of travel-time being used for other things;
- The additional cost of connected and autonomous technologies may change models of car ownership;
- The provision of *Mobility as a Service (MaaS)* may change the way in which trips are made; and,
- Associated improvements in technology, such as teleworking, reducing demand for travel.

This necessitates in-depth consideration of the drivers of travel demand, the potential changes and the ramifications for the future. A strategic modelling exercise, considering both supply-side and demand-side economics is best placed to take this work forward.

6.2.5. Implications for scheme appraisal

Drawing together all of these themes, there is a need to consider the implications for appraisal of highway and other transport schemes. The nature and spend of large infrastructure projects the appraisal period may cover a period of 60 years after scheme opening. It is expected that connectivity and autonomy will permeate the vehicle fleet by this time, which as this study shows, may have significant impacts on traffic flow and road capacity. It is important that these implications are considered, ensuring the underlying evidence for appraisal is robust.

Appendices

Appendix A. VISSIM parameters

A.1. Longitudinal behaviour

Parameter	Type	Description
CC0 Standstill distance	Continuous variable	The desired distance between stopped vehicles (i.e. in a queue)
CC1 Headway time	Continuous variable	The gap (in seconds) that a vehicle keeps
CC2 Following variation	Continuous variable	The distance in addition to the allowed safety distance that is permissible before the vehicle-drive unit moves closer to the preceding vehicle
CC4 Negative following threshold CC5 Positive following threshold	Continuous variable	Control speed differences during car following (i.e. how the vehicle reacts to the change in speed of the preceding vehicle)
CC6 Speed dependency of oscillation	Continuous variable	Influence of distance on speed oscillation (the variation of speed around the desired speed)
CC7 Oscillation acceleration	Continuous variable	Influence of vehicle acceleration during car following oscillation
CC8 Standstill acceleration	Continuous variable	Desired acceleration when starting from standstill
CC9 Acceleration at 80km/h	Continuous variable	Desired acceleration from a speed of 80km/h
Smooth closeup behaviour	Binary selection	Vehicles slow down more evenly when approaching a standing obstacle

A.2. Lateral behaviour

Parameter[28]	Type	Description
LC1: Maximum deceleration (driver and trail vehicle)	Continuous variable	The maximum deceleration of the driver or trail vehicle
LC2: -1 m/s^2 per distance (driver and trail vehicle)	Continuous variable	The maximum deceleration is reduced with increasing distance from the emergency stop position (in m – the distance at which this acceleration is applied)
LC3: Accepted deceleration (driver and trail vehicle)	Continuous variable	The initial deceleration taken by the driver or trail vehicle
LC4: Min headway (front/rear)	Continuous variable	The minimum distance separation to the vehicle in front that must be available for a lane change (in standstill)
LC5: Safety distance reduction factor	Bounded fraction	The proportion by which the safety distance is reduced during the lane changing manoeuvre (after completion the safety distance is implemented)
LC6: Maximum deceleration for cooperative braking	Continuous variable	The rate at which trailing vehicles decelerate in a cooperative braking situation
MG1: Minimum time gap	Continuous variable	Merging behaviour parameter to measure the minimum time gap for vehicle on the mainline to reach the minimum headway with its present speed
MG2: Minimum headway	Continuous variable	Merging behaviour parameter to measure the minimum acceptable headway to merge into the mainline

A.3. Connectivity

Parameter	Type	Description
Look ahead distance Observed vehicles	Continuous variable	The distance that can vehicle can see forward on the link
Look back distance	Continuous variable	As above, but relating to vehicles behind

[28] "LC" and "MG" identifiers are used for the purposes of this work, and are not VISSIM standard nomenclature

Appendix B. Model parameter variations

Capability level		CC0 (m)	CC1 (s)	CC7 (m/s^2)	CC8 (m/s^2)	CC9 (m/s^2)	LC4 (m)	LC5	MG1 (s)	MG2 (m)
Level II		1.5	0.9	0.25	3.5	1.5	0.5	60%	3	5
Level III	*Cautious*	2.5	1.8	0.10	3.2	1.2	0.8	90%	3.6	6.5
	Normal Cautious	2	1.2	0.20	3.4	1.4	0.6	70%	3.2	5.5
	Normal Assertive	1.0	0.8	0.30	3.6	1.6	0.4	50%	2.8	4.5
	Assertive	0.5	0.6	0.40	3.8	1.8	0.2	30%	2.4	3.5
*Level IV**		0.5	0.6	0.40	3.8	1.8	0.2	30%	2.4	3.5

*Level IV CAVs are subject to a fixed desired speed distribution based on the defined speed limit of the link. Other CAVs and the legacy fleet are subject to the (standard) desired speed distribution according to link type in VISSIM.

Appendix C. Summary results tables

C.1. SRN model, peak period

Scenario	Average delay (s)		Average journey time (s)		Journey time variability (s)		Coefficient of variation	
	(s)	%	(s)	%	(s)	%		%
Base	35.84	-	539.79	-	20.17	-	0.0374	-
(1) 25% CAV	36.17	*+0.9%*	538.49	*-0.2%*	19.38	*-3.9%*	0.0360	*-3.7%*
(2) 50% CAV	33.39	*-6.8%*	533.62	*-1.1%*	17.65	*-12.5%*	0.0331	*-11.5%*
(3) 75% CAV	29.77	*-16.9%*	527.72	*-2.2%*	15.33	*-24.0%*	0.0291	*-22.3%*
(4) 100% CAV	23.72	*-33.8%*	517.77	*-4.1%*	10.52	*-47.9%*	0.0203	*-45.7%*
(5) Upper bound	21.38	*-40.3%*	479.29	*-11.2%*	9.14	*-54.7%*	0.0191	*-49.0%*

C.2. SRN model, non-peak period

Scenario	Average delay (s)		Average journey time (s)		Journey time variability (s)		Coefficient of variation	
	(s)	%	(s)	%	(s)	%		%
Base	17.82	-	519.97	*0.0%*	6.62	-	0.0127	-
(1) 25% CAV	17.51	*-1.7%*	518.65	*-0.3%*	5.37	*-19.0%*	0.0103	*-18.8%*
(2) 50% CAV	17.06	*-4.2%*	516.21	*-0.7%*	5.78	*-12.7%*	0.0112	*-12.1%*
(3) 75% CAV	16.47	*-7.6%*	512.82	*-1.4%*	5.76	*-13.1%*	0.0112	*-11.9%*
(4) 100% CAV	15.79	*-11.4%*	507.32	*-2.4%*	6.53	*-1.4%*	0.0129	*1.0%*
(5) Upper bound	14.65	*-17.8%*	472.09	*-9.2%*	6.27	*-5.3%*	0.0133	*4.3%*

C.3. Urban model, peak period

Scenario	Average delay (s)		Average journey time (s)		Journey time variability (s)		Coefficient of variation	
	(s)	%	(s)	%	(s)	%		%
Base	65.91	-	277.78	-	88.38	-	0.3182	-
(1) 25% CAV	57.70	*-12.4%*	219.52	*-21.0%*	19.74	*-77.7%*	0.0899	*-71.7%*
(2) 50% CAV	54.44	*-17.4%*	205.35	*-26.1%*	10.01	*-88.7%*	0.0488	*-84.7%*
(3) 75% CAV	51.89	*-21.3%*	198.72	*-28.5%*	7.24	*-91.8%*	0.0364	*-88.6%*
(4) 100% CAV	48.02	*-27.1%*	192.64	*-30.7%*	6.00	*-93.2%*	0.0312	*-90.2%*
(5) Upper bound	46.36	*-29.7%*	184.25	*-33.7%*	5.71	*-93.5%*	0.0310	*-90.3%*

C.4. Urban model, non-peak period

Scenario	Average delay (s)		Average journey time (s)		Journey time variability (s)		Coefficient of variation	
	(s)	%	(s)	%	(s)	%		%
Base	53.49	*0.0%*	209.25	*0.0%*	10.80	*0.0%*	0.0516	*0.0%*
(1) 25% CAV	52.00	*-2.8%*	203.18	*-2.9%*	7.50	*-30.5%*	0.0369	*-28.4%*
(2) 50% CAV	50.59	*-5.4%*	198.11	*-5.3%*	6.53	*-39.6%*	0.0329	*-36.2%*
(3) 75% CAV	48.65	*-9.1%*	194.06	*-7.3%*	6.32	*-41.5%*	0.0326	*-36.9%*
(4) 100% CAV	45.65	*-14.7%*	189.43	*-9.5%*	5.37	*-50.3%*	0.0284	*-45.1%*
(5) Upper bound	44.19	*-17.4%*	180.47	*-13.8%*	5.36	*-50.4%*	0.0297	*-42.5%*

Appendix D. Modelled journey times

D.1. Journey time summary – SRN model, segment JTa

Scenario	Average travel time (s)	Max travel time (s)	Standard deviation (s)	Sample size
All vehicles				
Base	539.8	600.6	20.2	42203
25%	538.5	599.5	19.4	42296
50%	533.6	581.9	17.7	42137
75%	527.7	574.2	15.3	42039
100%	517.8	550.4	10.5	42160
Upper bound	479.3	508.4	9.1	42269
Legacy fleet				
Base	539.8	600.6	20.2	42203
25%	538.6	601.1	19.6	31648
50%	535.4	581.6	17.5	21152
75%	531.7	581.9	16.3	10610
100%	-	-	-	-
Upper bound	-	-	-	-
CAVs				
Base	-	-	-	-
25%	538.4	598.4	20.5	10548
50%	531.9	583.7	18.8	20814
75%	526.4	571.8	15.7	31074
100%	517.8	550.4	10.5	40960
Upper bound	479.3	508.4	9.1	42269

D.2. Journey time summary – SRN model, segment JTb

Scenario	Average travel time (s)	Max travel time (s)	Standard deviation (s)	Sample size
All vehicles				
Base	202.8	317.4	50.3	53090
25%	207.1	343.8	55.8	53052
50%	198.9	345.1	51.4	53055
75%	187.2	355.1	42.9	53091
100%	166.6	180.4	6.0	53060
Upper bound	151.5	173.6	6.7	53051
Legacy fleet				
Base	202.8	317.4	50.3	53090
25%	207.4	345.3	56.1	39765
50%	199.8	344.5	51.8	26614
75%	188.6	364.0	43.6	13365
100%	-	-	-	-
Upper bound	-	-	-	-
CAVs				
Base	-	-	-	-
25%	206.1	339.0	55.1	13178
50%	198.1	345.8	51.0	26143
75%	186.7	353.3	42.6	39267
100%	166.6	180.4	6.0	51533
Upper bound	151.5	173.6	6.7	53051

D.3. Journey time summary – urban model

Scenario	Average travel time (s)	Max travel time (s)	Standard deviation (s)	Sample size
All vehicles				
Base	277.8	562.6	88.4	10841
25%	219.5	296.0	19.7	10887
50%	205.3	238.9	10.0	10913
75%	198.7	226.7	7.2	10881
100%	192.6	213.0	6.0	10894
Upper bound	184.2	200.3	5.7	10899
Legacy fleet				
Base	273.1	564.6	90.4	10601
25%	214.7	298.0	21.8	7978
50%	200.7	238.3	11.0	5370
75%	193.2	233.1	9.2	2646
100%	-	-	-	-
Upper bound	-	-	-	-
CAVs				
Base	-	-	-	-
25%	210.2	271.8	18.4	2669
50%	197.3	236.1	11.2	5303
75%	192.0	223.8	8.1	7995
100%	186.0	207.9	6.4	10654
Upper bound	177.4	194.0	6.0	10659

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