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

Stage 2: Traffic Modelling and Analysis Technical Report

Department for Transport

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1. Introduction

The Department for Transport (DfT) 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 consisted 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 and road capacity.

This report details the work undertaken as part of Stage 2. It is divided into five chapters, containing the following elements:

- An introductory chapter, providing context and specifying the research objectives (Chapter 1);
- The methodology chapter, detailing the specific technical approach undertaken (Chapter 2);
- A chapter describing the design, build and implementation of simple network models (Chapter 3);
- A chapter describing the design, build and implementation of complex network models (Chapter 4);
- Conclusions drawn from this study, limitations and recommendations for further work (Chapter 5).

This report is technical in nature, and assumed some familiarity with microsimulation modelling and traffic engineering.

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 to inform policy making.

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 capacity, junction capacity and network service level.

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:

- Changed accelerating and decelerating behaviour;
- Changed longitudinal behaviour when following other vehicles,
- Changed lateral behaviour and gap acceptance thresholds; and,
- Changed decision making due to better provision of information.

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 capacity gain. 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 objective of Stage 2 of this project is therefore aiming to quantify the potential impacts of CAVs on traffic flow and road capacity, including a wide range of scenarios with:

- Combinations of network elements and road types;
- Various market penetrations of CAVs;
- Demand situations; and,
- Vehicle capabilities in autonomy and connectivity.

Whilst specific to the UK road network, the findings here are transferrable in an international context.

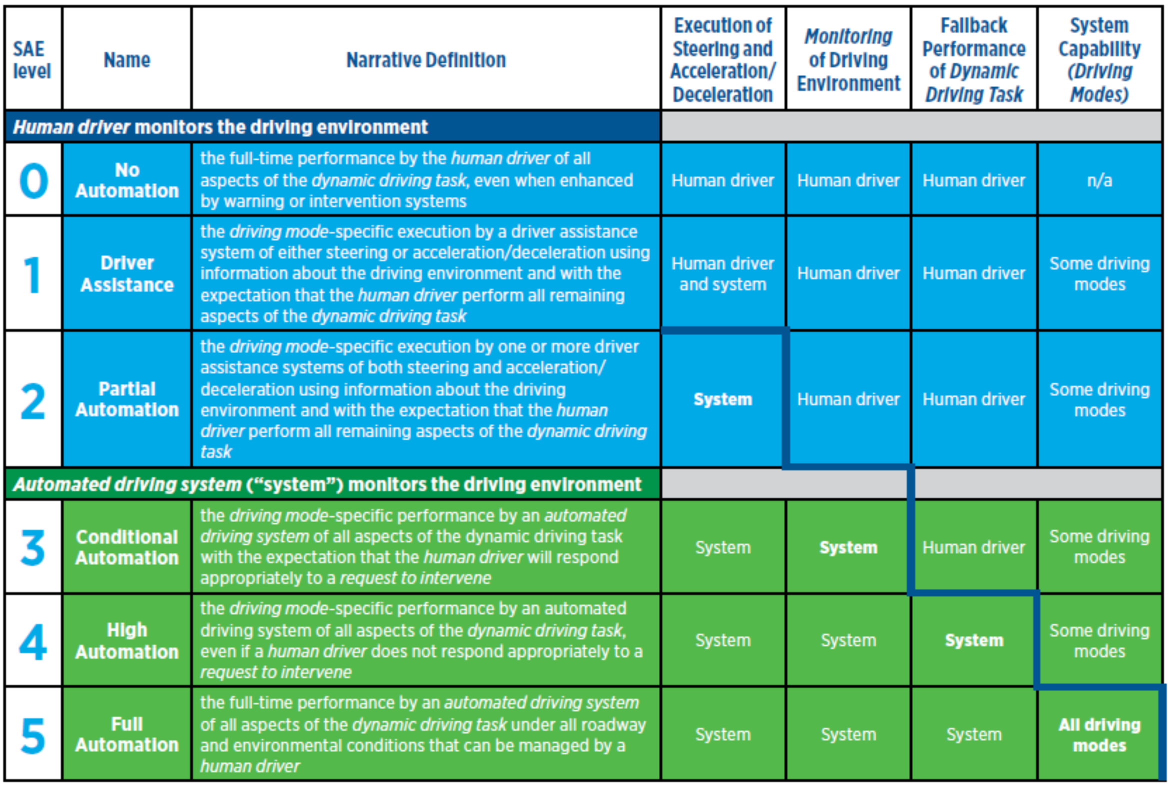
1.2. Definitions

It is recognised that multiple definitions are available concerning connected and autonomous vehicles. The DfT's detailed regulatory review, "The Pathway to Driverless Cars"[1] 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[2], 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.

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

[2] 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.

Common definitions relating to traffic flow and road capacity will be used throughout. **Capacity** is 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. Further definitions will be given where relevant.

2. Methodology

This chapter described the technical approach adopted in this project. This covers the methodology only, with subsequent chapters discussing the traffic networks and scenarios to be implemented.

2.1. Modelling approach

The general approach adopted in this project is to proxy the effects of connected and autonomous vehicles in an existing traffic microsimulation software package. This work has used PTV VISSIM 8, hereafter referred to as VISSIM.

VISSIM is a microscopic level traffic simulation package which looks at the movement of individual vehicles in the traffic. The physical movement and psychological decision making process of each driver is determined in response to other vehicles and infrastructure. VISSIM contains several stochastic elements, but does not (in the main) extend to "incidents" as related to safety and non-compliance with traffic regulations.

As discussed in Chapter 1, this project is concerned with the impacts on the movements of individual vehicles and how that in turn impacts macroscopic characteristics of traffic flow. As such, trip generation, distribution, mode choice and travel demand modelling in general are outside of the scope of this work.

The basic principles of how connected and autonomous vehicles may impact *microscopic* traffic flow and capacity are related to the mechanics of vehicle operation. This is supported by the outputs of the Stage 1 evidence review, including discussion with wider industry and recognised experts. The major mechanisms of action identified in Stage 1 of this project are:

- Longitudinal spacing of vehicles;
- Acceleration and deceleration behaviour of vehicles; and,
- Lateral gap acceptance.

In VISSIM, vehicles move laterally and/or longitudinally. Suitable parameters have been identified that allow for the representation of modified behaviour of connected and autonomous vehicles. VISSIM allows for the manipulation of base vehicle parameters and the definition of vehicle "types". Basic characteristics of vehicle dynamics can be manipulated through "driving behaviour parameter sets"[3]. This sections considers the modification of vehicle behaviour in three different ways:

- Autonomy-effected longitudinal movement;
- Autonomy-effected lateral movement; and,
- Connectivity.

Whilst the generic term "vehicle" is used here, this could equally apply to passenger cars, goods vehicles or public transport vehicles.

2.1.1. 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 1.

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[3] A major reference for this work is VISSIM user documentation, produced by PTV

Table 1: 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.

In each of these driving modes, the behaviour of the vehicle may be changed as a result of enhanced technology. For example, the “free driving” mode of operation recognises oscillation around desired speed due to imperfect throttle control. This may be eliminated as a result of vehicle autonomy.

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 **speed function and distribution** components of VISSIM. In VISSIM, car-following parameters are determined by using a built-in model, which can be selected as either the Wiedemann 74 or Wiedemann 99 car-following model. As Wiedemann 99 provides more adjustable parameters to describe the car-following behaviour which could be utilised to manipulate the driving behaviour, it has been adopted in this study, and a full list of parameters is given in Appendix A.

Table 2 shows the car-following parameters chosen for variation to represent (by proxy) the behaviour of autonomous vehicles in VISSIM.

Table 2: Longitudinal movement parameters (adapted from VISSIM documentation)

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

Desired safety distance is an important factor in the longitudinal movement behaviour in VISSIM, which determines the minimum distance each driver will try to keep during car-following. At a given speed, the desired safety distance is calculated as a function of the standstill distance (CC0), the headway time (CC1) and the current speed (v) of the vehicle itself. This is the key avenue by which the behaviour of connected and autonomous vehicles can be replicated within VISSIM.

In terms of speed and derivatives of speed, VISSIM does not adapt a single value, but rather uses distribution functions to replicate the range of different behaviour expected. It is conceivable that behaviour will become more homogenous across the vehicle fleet with the implementation of CAVs. However, given the likely range of manufacturers and the “user choice” expected to be available, there is insufficient evidence with which to determine a different distribution for CAVs[4]. It should be noted that speed and acceleration (particularly concerning imperfect throttle control) can be adapted via the parameters listed in Table 2.

2.1.2. Lateral movement

Lateral movement in VISSIM incorporates behaviour within (termed “lateral behaviour”) and between (termed “lane change”) lanes, as well as merging from minor road to the major road traffic (termed “merging”).

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[4] As this refers to a distribution, modification of these functions does represent enhanced capability of an individual vehicle

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[5].

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 (CC0 + CC1 * v) must be achieved/maintained as part of the manoeuvre.

Merging behaviour is established when a vehicle on a minor road wants to merge to the traffic on the mainline, or in a lane drop situation. Priority will be given and the gap acceptance of drivers are considered.

The "aggressiveness" of behaviour can be adapted for lane change and merging behaviour through a series of available parameters, as shown in Table 3.

Table 3: Lane changing behaviour in VISSIM (adapted from VISSIM documentation)

Parameter	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

LC1, LC2 and LC3 combine to give the profile deceleration behaviour as a vehicle changes lanes. LC4 and LC5 are related to decision making (i.e. if a lane change can take place). In both cases, the expectations around potential behaviour of CAVs is similar to that of longitudinal movements: CAVs will have the technology enabling "smoother" behaviour; CAVs will have the technology enabling smaller gaps (time, distance) to be accepted.

MG1 and MG2 are related to the decision making when vehicles on minor roads try to merge onto the main (with priority) track. Both parameters are considered to give "gap acceptance", and the vehicle on the minor

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

road will make a merging decision according to its own gap acceptance, as well as the speed and the location of the next conflicting vehicle on the main road.

2.1.3. Connectivity

There is no explicit representation of vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication 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. Driver behaviour parameters which may be varied to proxy connectivity are shown in Table 4.

Table 4: Parameters to proxy connectivity

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

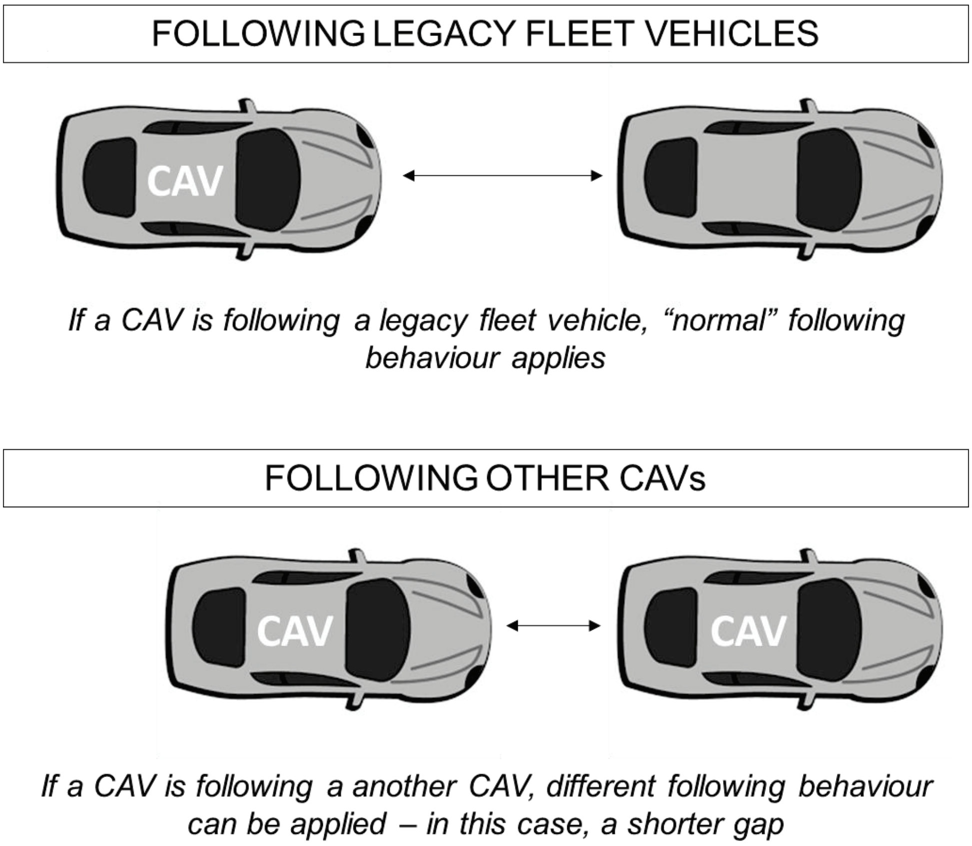
All parameters discussed in this chapter so far reference the behaviour of an individual vehicle and for the duration of the simulation period. In order to proxy potential vehicle-to-vehicle and vehicle-to-infrastructure, vehicles in the model must be able to change their behaviour dynamically according to information provided by the surrounding environment. As the traditional microsimulation environment does not provide such a feature, the VISSIM COM interface is utilised in this case.

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

Figure 1: Connectivity and following behaviour



If a CAV is following a legacy fleet vehicle, "normal" following behaviour applies

If a CAV is following a another CAV, different following behaviour can be applied – in this case, a shorter gap

In this simple example, the trailing CAV adopts different behaviour based on the characteristics of the lead vehicle. This functionality allows platoons to form "naturally", with a chain of connected and autonomous vehicles following at short intervals.

The actual logic adapted as part of this study is explained in subsequent chapters.

2.1.4. CAV modelling approach summary

PTV VISSIM 8 will be used to replicate the behaviour of CAVs in a simulation environment. The key mechanisms for achieving this will be:

- Change in longitudinal movement through modification of various parameters of the Wiedemann 99 car-following model;
- Change in lateral movement through modification of lane change behaviour and gap acceptance parameters; and,
- Representation of connectivity through broad parameter changes and implementation of a dynamic behaviour change mechanism.

In order to account for the stochastic nature of traffic, in each case a number of "random seeds" will be used. This has been set at 10 to provide a balance between introducing enough variation in the results and presenting a practical number of simulation model runs.

2.2. Testbed models

Given the complex nature of the road network, and the uncertainty concerning the capability of connected and autonomous vehicles, various testbed models have been developed to investigate the potential impacts of CAVs in different traffic situations.

A two-stage approach is advocated for this study, and the elements included are described in this section.

Simplified link and junction models

The use of simple link and junction models allows the effects of particular parameters to be isolated and capacity to be evaluated for a given situation. Whilst these simplified models should be relevant to the UK (i.e. designed and constructed to the relevant standards) they should not include the complexities and interactions of particular sites which may make the interpretation of results more difficult.

Complex, real-world situations

Particular "packages" of measures and infrastructure scenarios can then be implemented in a limited number of real-world models. These allow the interaction of different areas of the strategic and urban road networks to be investigated in greater detail.

2.2.1. Simple models

Five simple model builds have been identified, allowing for focus on particular aspects of vehicle dynamics and driver behaviour. These models are summarised in Table 3, alongside the (increasingly complex) behavioural focus.

Table 5: 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)

2.2.2. Complex models

To investigate the combination of particular behavioural changes, two complex models will be used. Whilst based on real-world situations, these models are purposefully not site-specific, time-specific or purpose-specific, and therefore are not subject to calibration and validation as would be required for scheme appraisal. These models will instead by representative of the UK network, consistent with key modelling guidelines, and above all, fit for the purposes of this work[6].

These are a strategic road network (SRN) model, and an urban model. The elements included in each are shown in Table 6.

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[6] For example, models will utilise the more flexible Wiedemann 99 car-following model as opposed to the (often used) Wiedemann 74 model.

Table 6: Scope of complex models

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

In order to ensure accurate geometry and road layouts, these networks have been initially built according to specific parts of the UK road network. The intention is to provide a suitable base model for this assessment which is representative of the UK road network.

2.3. Measures of performance

When utilised for design and appraisal, microsimulation models provide several different types of output as relating to traffic network performance. These include:

- Capacity;
- Delay;
- Speed; and,
- Journey time.

This section discusses the different types of output available and summarises those most suitable for the base models assessment. Alongside this, this section introduces fundamental theories of traffic relevant to this work, providing example outputs.

2.3.1. Network performance metrics

In a general traffic context, capacity is defined as the maximum sustainable flow of traffic passing in 1 hour, under favourable road and traffic conditions[7]. For the purposes of this study, capacity is defined as the maximum **attainable** flow, expressed in units of vehicles/hour, but evaluated over a shorter time period. Whilst appropriate for the constrained situations of the simple models, capacity is not a useful or easily defined metric for the complex models. Therefore alternate measures of network performance are required.

Delay within VISSIM is calculated as the difference between the theoretical attainable travel time and the actual travel time. This incorporates delay caused by congestion (other vehicles) and traffic control, but does not include geometric delay.

Average speed, delay and journey time metrics are often used to differentiate between options in design and appraisal of road network schemes. In this case, they can be used to differentiate between performance of the vehicle fleet.

2.3.2. Traffic flow theory

Aspects of fundamental traffic flow theory may also be used to explain performance. Macroscopic models of traffic flow relate three fundamental variables: speed (v), flow (q) and density (k) in the form $q = k*v$. The

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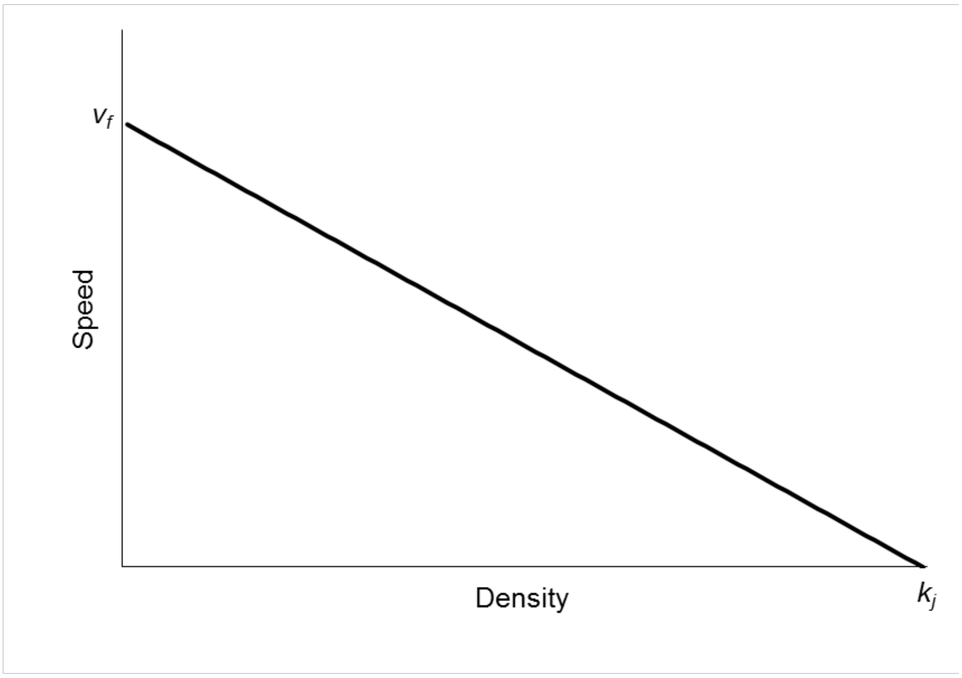
[7] DMRB Volume 5 Section 1 (TA 79/99)

formulation of this specifies speed and density as independent (explanatory) variables, and flow as the dependent variable.

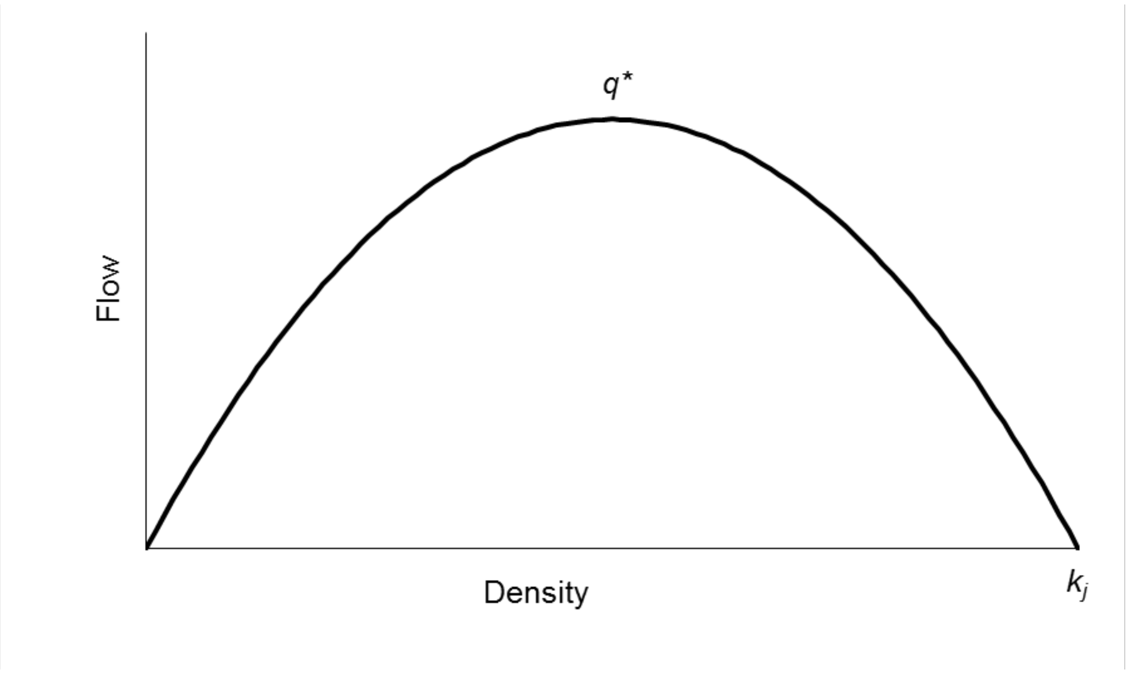
These relationships have been formalised in (several) mathematical models determined through empirical measurement. One such example is the Greenshields model, where there is a linear relationship between speed and density, as per Figure 2. This relationship is characterised by v_f, the free-flow speed, and k_j, the jam density.

Figure 2: Linear speed-density relationship



As density of traffic increases (i.e. more vehicles on the road), speed tends towards zero. Combining the fundamental relationship q = k*v and the linear speed-density relationship produces the quadratic flow density relationship, as shown in Figure 3.

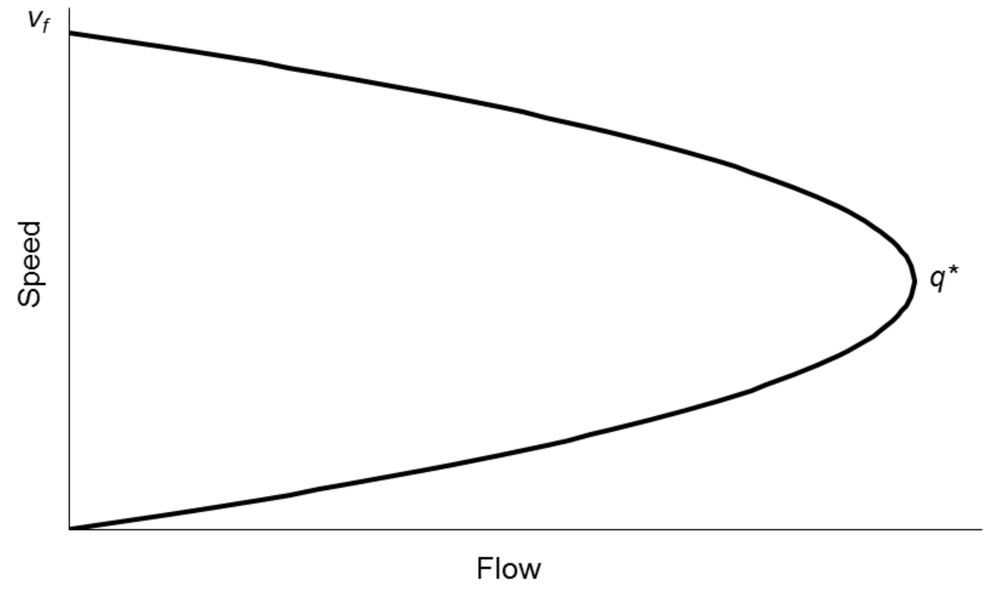
Figure 3: Flow-density relationship



Flow, q, tends to zero at zero density (and so k = 0 and v_f is realised) and at jam density (k_j). As such, definition of k_j and v_f (for a given system) obtain q*, the maximum flow.

The third fundamental relationship is between speed and flow, as shown in Figure 4.

Figure 4: Speed-flow relationship



Whilst these fundamental diagrams are idealistic (particularly the basis of a simplistic linear relation between speed and density), the characteristic shape of the speed-flow relationship is generally seen in empirical data for a heterogeneous vehicle fleet.

In order to influence the maximum capacity, q*, a change is required to the limiting factors or k_j or v_f. In this work, the jam density is changed (directly or indirectly) due to modification of (microscopic) vehicle behaviour, and the relationship between density and speed is altered. The impacts of this on these macroscopic relationships, through either speed-flow or flow-density diagrams, is a useful output, providing a deeper understanding of the CAV fleet on a given link than a single metric for capacity is able.

3. Simple models

Table 5 (Section 2.2) introduced five simple models, denoted by the letters A-E. These models investigate particular behaviours of increasing complexity. This section covers the construction of the simple model networks, definition of scenarios, simulation results and discussion of the impacts.

3.1. Simple model build

All models have been constructed in VISSIM 8, using standard link types and UK relevant rules of operation. The models have been scrutinised with various levels of traffic demand to ensure the behaviour is applicable to the situations they are designed to represent.

3.1.1. Model A – single-lane link

Model A is a single-lane link model designed to isolate the impacts of changes in longitudinal vehicle spacing, such as vehicle headway. The model consists of one straight single-lane unidirectional link with a length of 1km and a speed limit of 60mph. The model does not have any traffic control or interaction with other infrastructure, as show in Figure 5 and Figure 6.

Figure 5: Overview of Model A, single-lane link

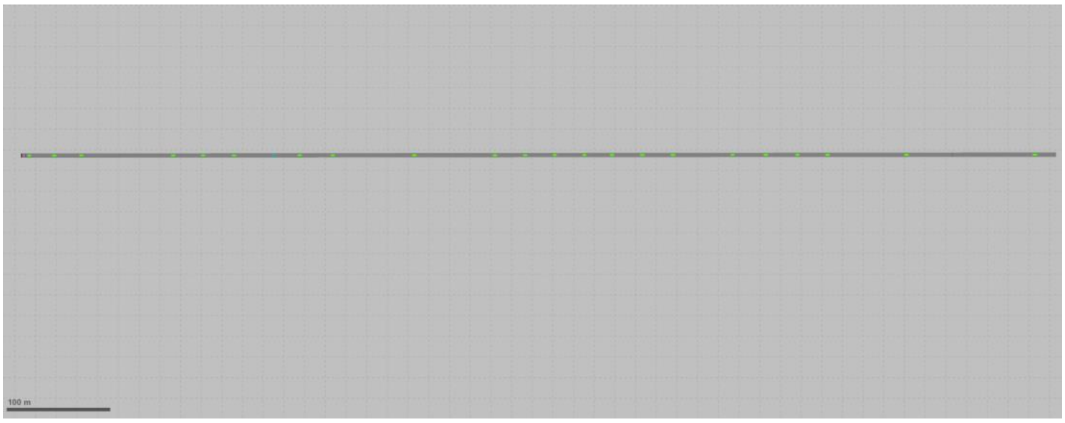
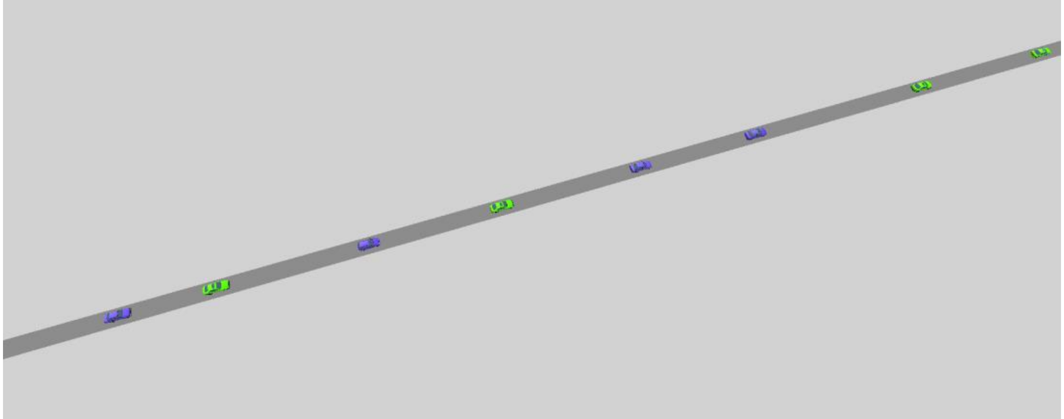


Figure 6: Detailed view of Model A, single-lane link



3.1.2. Model B – multi-lane link

Model B is a multi-lane link model, consisting of a 1km two-lane uni-directional link and a speed limit of 70mph. Vehicles are free to make lane changes between the two lanes. This model therefore considers both longitudinal and lateral behaviours for various levels of CAV capability by incorporating lane-changing movements in the form of overtaking manoeuvres. The model is shown in Figure 7 and Figure 8.

Figure 7: Overview of Model B, multi-lane link

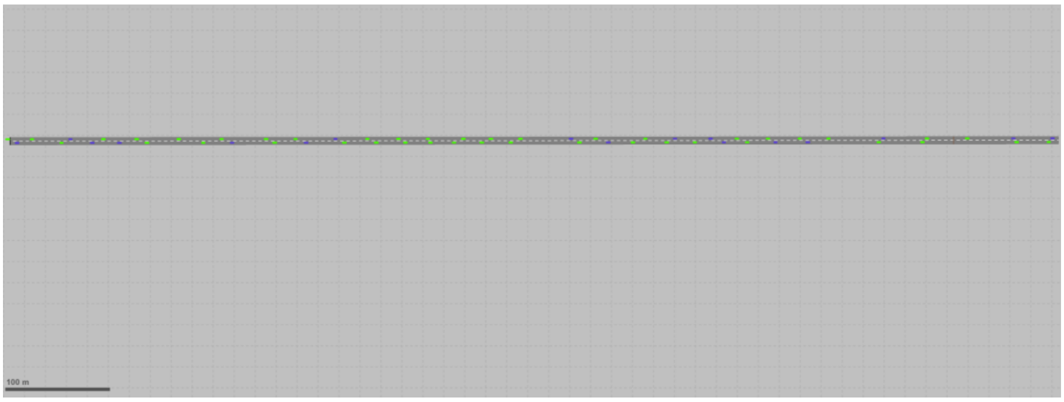
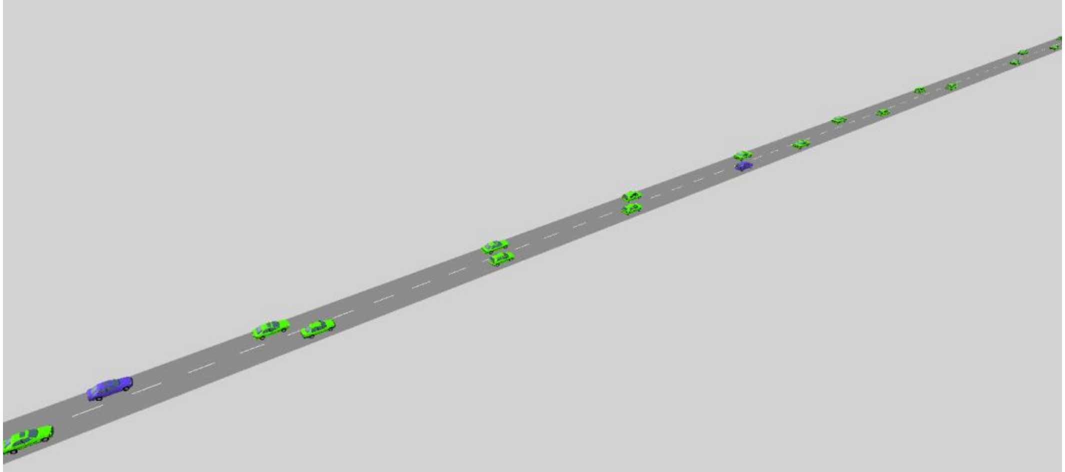


Figure 8: Detailed view of Model B, multi-lane link



3.1.3. Model C – signalised junction

Model C considers the impacts of CAVs with different longitudinal behaviour and acceleration/deceleration from/to standstill. It consists of a four-arm signalised junction with a speed limit of 30 mph. Each arm of the junction is 0.5km in length, making the total travel distance of each vehicle 1km. This model is shown in Figure 9 and Figure 10.

Figure 9: Overview of Model C, signalised junction

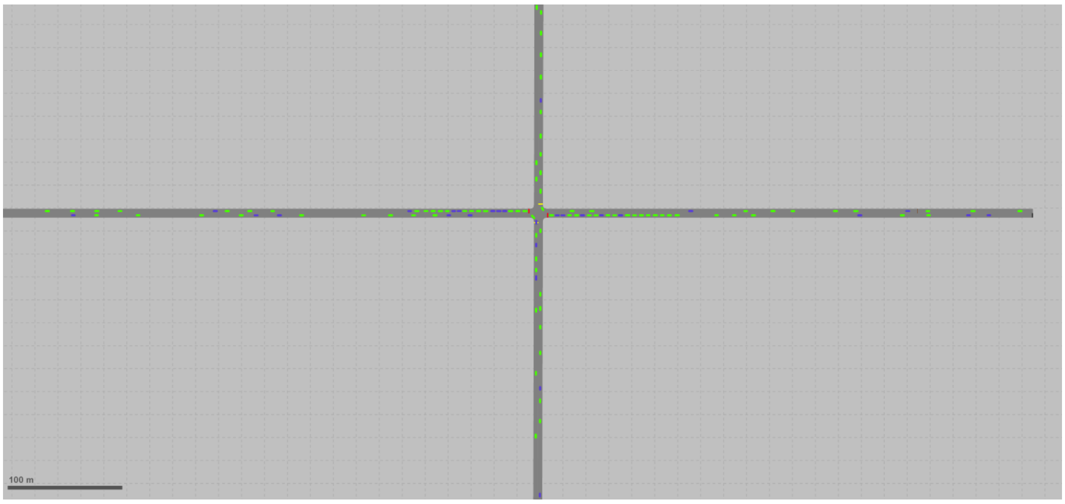
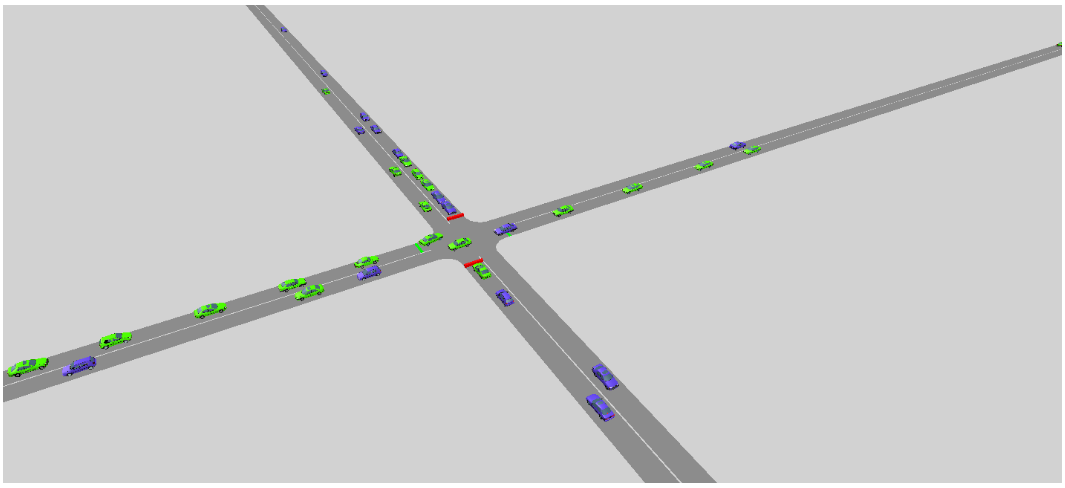


Figure 10: Detailed view of Model C, signalised junction



Total cycle time of the junction has been set to 88 seconds with 2 stages, with each stage given 7 seconds of intergreen time and 37 seconds of green time for ahead and left turn traffic. This model has been set up in line with UK junction design guidance. As this model does not consider gap acceptance, right turning movements for all 4 arms are banned to reduce the influence of this behaviour. This is also consistent with design and operation of a saturated junction, particularly in urban areas where alternate routes exist.

3.1.4. Model D – roundabout

Model D introduces gap acceptance alongside longitudinal behaviour for vehicles on a roundabout. The model is a four-arm roundabout (speed limit 40mph) with a single circulatory lane and an inscribed circle diameter of 30 metres. Vehicles enter the roundabout based on the gap acceptance of the driver, and will give priority to circulating traffic.

The entry and exit lanes of the roundabout are all single-lane link with 500m before approaching/after leaving the roundabout, which makes the total journey length of approximately 1km for each vehicle.

Figure 11: Overview of Model D, roundabout

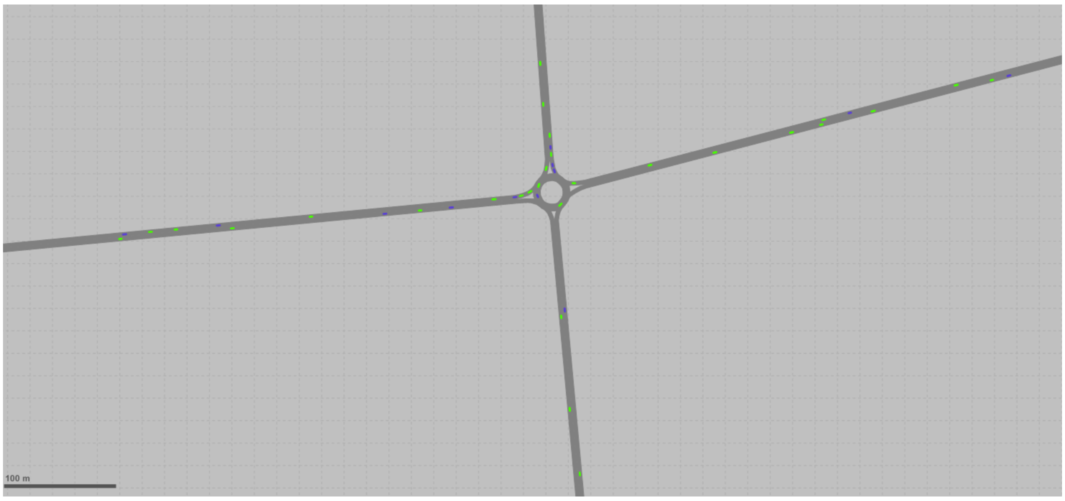
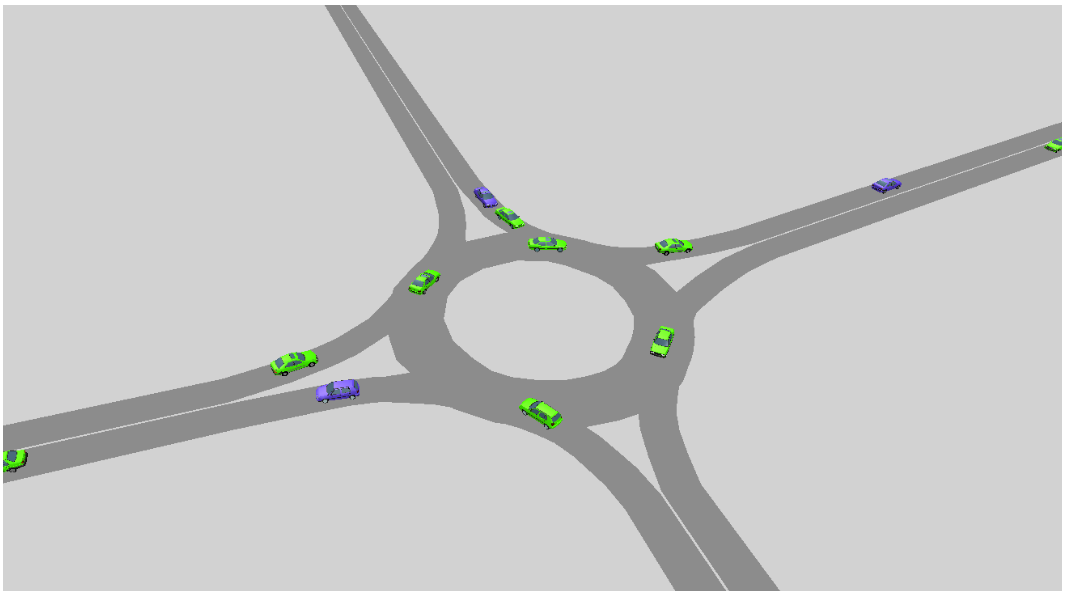


Figure 12: Detailed of Model D, roundabout



3.1.5. Model E – multi-lane link with merge

Model E aims to investigate the impact of CAVs on longitudinal gap, lateral movement and gap acceptance in high speed traffic flow (for example, to motorway or expressway standard). The merge consists of a dual carriageway and a single-lane on-ramp link to a three-lane section for 200m, followed by a lane drop to two continuing lanes. This model is shown in Figure 13 and Figure 14.

Figure 13: Detailed of Model D, multi-lane link with merge

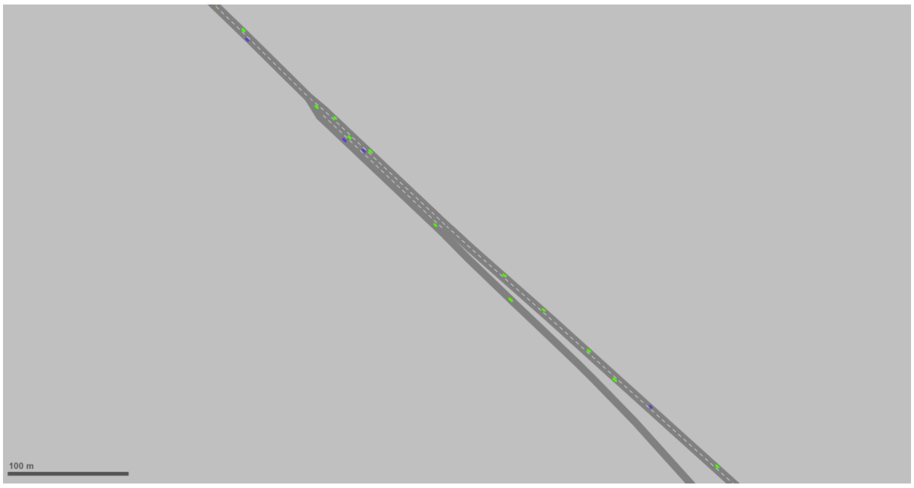
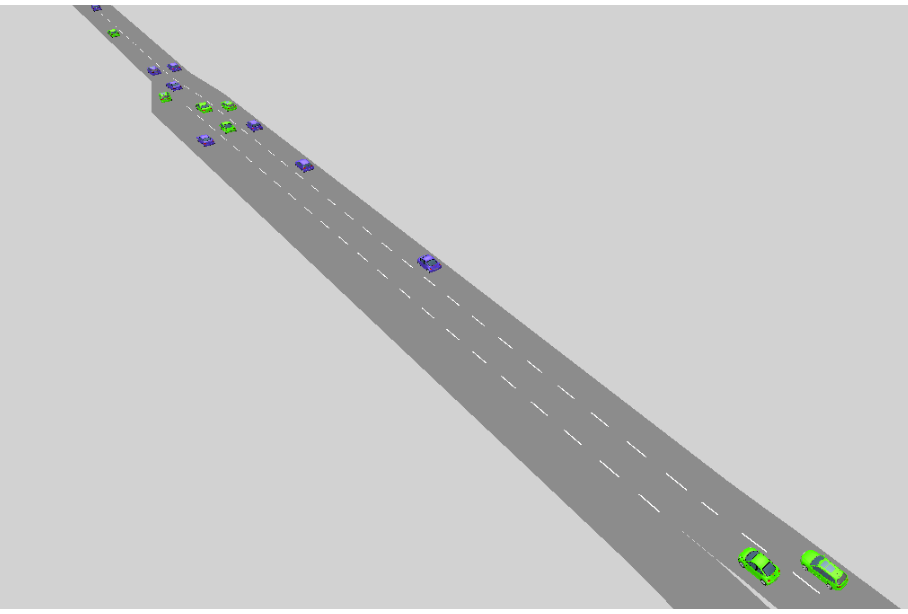


Figure 14: Detailed of Model E, multi-lane link with merge



3.2. Scenarios

This section discusses the scenarios employed in the simple network models, designed to test the impacts of changes to particular behaviour changes that may be brought about by increasing autonomy and connectivity in the vehicle fleet.

The scenarios defined for use in the simple network models involve a combination of the following features:

- CAV capabilities;
- CAV fleet penetrations; and,
- Traffic demand.

Each of these will be described in the following sub-sections.

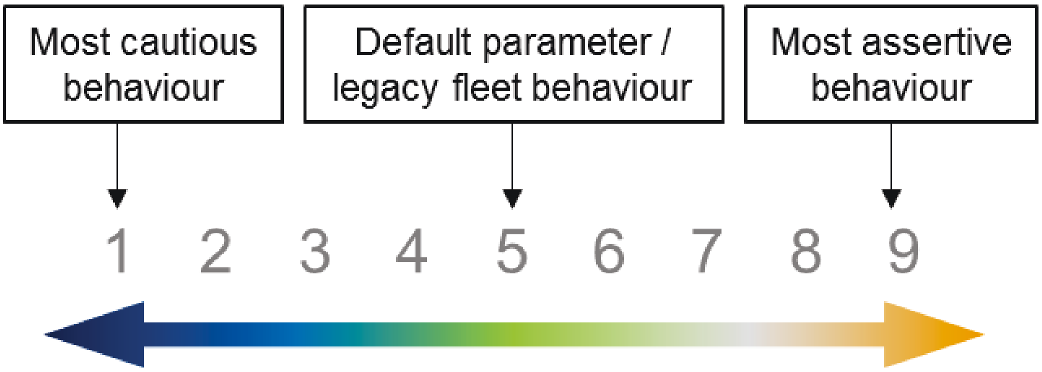
3.2.1. CAV capability

It is assumed that CAV are manufactured to be able to provide driving behaviour options in order to suit different drivers, who may setup CAVs to fit their own driving behaviour. For example, more assertive drivers may have higher acceleration and keep shorter gaps, while cautious drivers may maintain longer distances from other vehicles.

CAV "capability" is defined here as the possible driving behaviour options available to the user whilst obeying traffic regulations, such as speed limits and priority rules. Nine levels of CAV capability levels are defined to represent the potential assertive or cautious driving behaviours that CAV can be setup as by users. For each capability level, selected parameters will be changed for each simple model based on the targeted behaviour changes.

Whilst the actual set of parameter changes varies according to model (and the behaviour focus identified in Section 2.2.1 and Table 5), the general approach is to systematically vary behaviour to enable CAVs to be more cautious or more assertive than the legacy fleet. This general approach is shown in Figure 15.

Figure 15: Approach to varying CAV capability



The behaviour focus identified for the simple models may be considered more relevant to enhanced autonomous functions. In many cases the connectivity is therefore implicit; vehicle connectivity is required to achieve the required level of autonomy. To account for specific benefits that connectivity alone may provide, some global parameters are also altered, as shown in Table 7. These apply to all CAVs in the simple models, regardless of the scale of caution/assertiveness apparent.

Table 7 also includes four parameters relating specifically to improved throttle control (CC2, CC4, CC5, CC6). Again, these are assumed to be applicable to all CAVs.

Table 7: Global parameters applied to simple models

Parameter	Legacy fleet	CAV fleet
CC2 Following variation	4 m	0
CC4 Negative following threshold CC5 Positive following threshold	± 0.35	0
CC6 Speed dependency of oscillation	11.44 km/h	0
Look ahead distance Observed vehicles	4 vehicles	10 vehicles
Smooth closeup behaviour	No	Yes

For each simple model, Capability Level 5 will retain the same parameters as the legacy fleet, with the exception of the global parameters listed in Table 7.

Table 8 shows the parameters selected for varying in each simple model. These are described in more detail in Chapter 1 and Appendix A.

As discussed earlier in this section, these parameters combine to vary vehicle behaviour on a scale from “cautious” to “assertive”. For example, the safety distance (dx_{safe}) is defined by CC0 (the standstill distance, m) and CC1 (the headway time, s) as follows:

$$dx_{safe} = CC0 + CC1 \times v$$

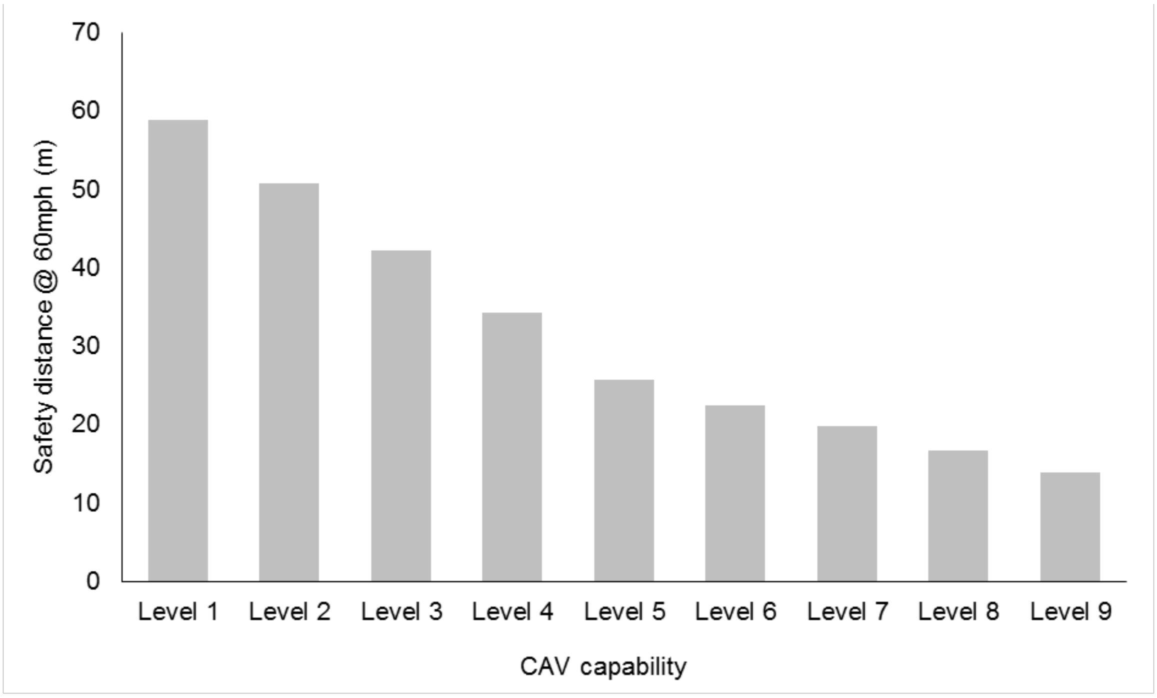
Table 8: Simple model parameter selections

Identifier	Model type	Parameter change
A	Single-lane link	CC0, CC1, CC7
B	Multi-lane link	CC0, CC1, CC7, LC4, LC5
C	Signalised junction	CC0, CC1, CC7, CC8
D	Roundabout	CC0, CC1, CC7, CC8, MG1, MG2
E	Multi-lane link with merge	CC0, CC1, CC7, CC8, CC9, LC4, LC5, MG1, MG2

Therefore the capability levels for each of the simple models can be described by the safety distance adopted by CAVs at a given speed. An example of the safety distance employed in Model A, single-lane link is shown in Figure 16. In this instance, Level 5 is the same capability as the legacy vehicle fleet (for the parameters in question).

It is also important to note that CAV capability levels may not vary linearly. For example, the difference in assertiveness between Level 9 and Level 5 is not the same as the difference between Level 5 and Level 1. This is because even though CAVs could potentially have enhanced capabilities, they will keep safety as the Similar calculations can be made for the capabilities employed in other simple models, such as the safety distance employed when changing lanes. A full list of parameter variations implemented in each simple model is shown in Appendix B.

Figure 16: Model A – CAV capability



3.2.2. Fleet penetration

Fleet penetration is defined as the percentage of vehicles that will operate as CAV in the total vehicle fleet. To consider a wide range of possible future cases, each capability level as defined in the simple model will be assessed with CAV penetration rates of 0%, 25%, 50%, 75% and 100%.

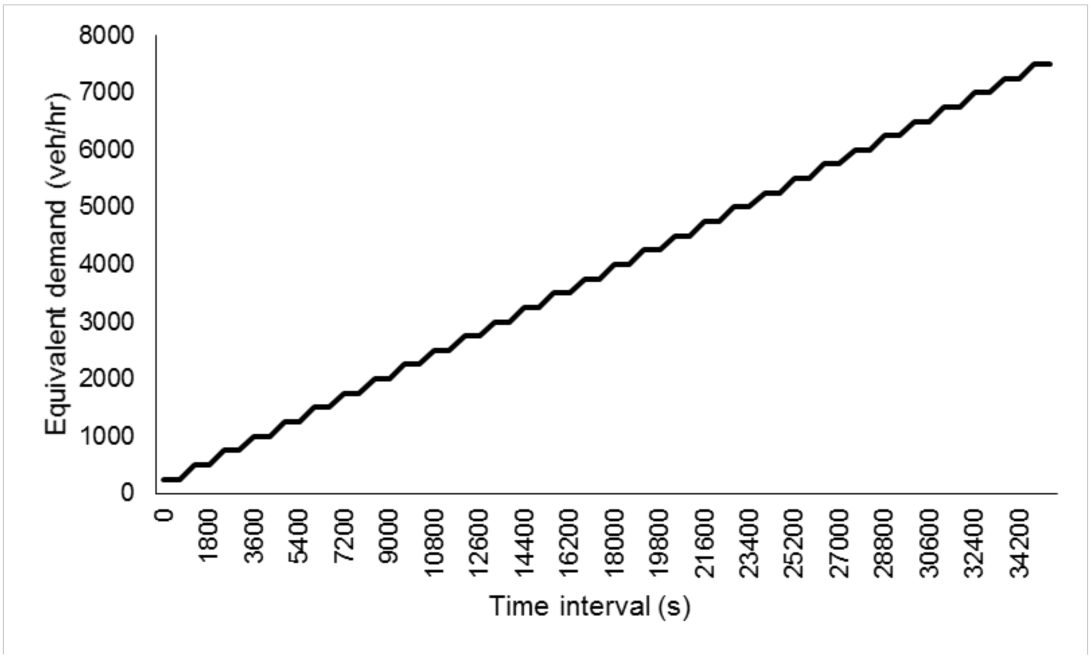
In a given model, only a single capability level will be investigated, and all vehicles will be of passenger car types. The rationale is to control the simple models as far as possible, allowing the effects of individual parameters to be tested. Multiplicative effects of different CAV capabilities and different vehicle fleet types will be explored further in the complex models (discussed in Section 4).

3.2.3. Traffic demand

In order to judge capacity implications of the varying CAV impact, it is necessary to vary demand and examine the resultant network performance. This will also allow the potential impacts of CAVs to be gauged for different operational scenarios (for example, peak and off-peak time periods).

Traffic demand levels are changed linearly over the course of the model run. Each demand level has 30 minutes time interval and demand profile ranges from a base level (e.g. 100 veh/hr) to the maximum attainable demand to ensure sufficient demand levels are captured. An example for Model B is shown in Figure 17.

Figure 17: Model B – demand profile



3.3. Results

This section provides the results obtained from the simple models (A-E). Impacts on traffic flow and road capacity of each of the simple models are discussed. Due to the large amount of data resulting from the model runs, additional outputs can be found in Appendix D.

Speed-flow relationship and flow-density relationship graphs are created for particular simple models. The data points from the 10 model runs of each penetration and each capability level are plotted, and best-fit trend lines are generated[8]. However, it is worth noting that the best-fit trend line cannot represent all data points, and there are still some residual points due to the randomness of the simulation.

3.3.1. Model A (single-lane link)

Model A is a single-lane link with a speed limit of 60mph. The focus of this model is purely longitudinal behaviour, with assertive CAVs driving more closely spaced.

Capacity

As there is no obstacle downstream of the link, network capacity (maximum attainable traffic flow) in Model A depends on safety distance and acceleration during car-following oscillation. Table 9 shows the impact on

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[8] The resultant R-squared value is scrutinised to ensure the trend is appropriate

capacity of varying levels of penetration and CAV capability. In all cases, the capacity is compared to the common base traffic flow of 0% CAV penetration.

The results are as expected. With enhanced longitudinal behaviour (levels 5 – 9), higher density can be obtained and hence greater capacity. This increases with penetration. When more vehicles accelerate faster and keep shorter distance when they are following another vehicle, capacity of the network is increased.

Conversely, where CAVs are more cautious than the existing vehicle fleet, deployment results in lower road capacity, with as much as a 40% reduction in capacity for cautious (level 1) CAVs at full fleet penetration (100%).

A further interesting result evident in Table 9 is the trade-off between penetration and capability. For example, approximately the same capacity impacts are obtained with a high penetration (75%) of a moderately assertive CAV (level 6) as compared to lower penetration (25%) of a highly assertive CAV (level 9).

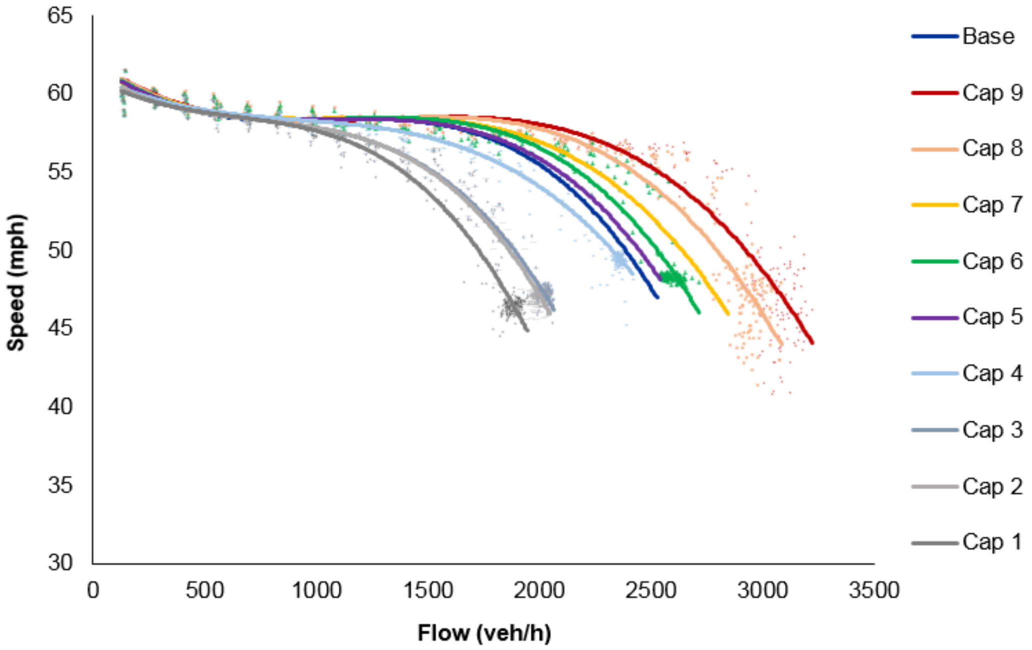
Table 9: Model A capacity impact

Percentage change from the base situation (0% CAV penetration)		**Penetration**			
		25%	**50%**	**75%**	**100%**
Capability	**1**	-11.4%	-22.4%	-31.4%	-38.5%
	2	-7.9%	-17.5%	-25.8%	-32.4%
	3	-7.5%	-16.8%	-24.7%	-31.2%
	4	-0.1%	-3.2%	-7.1%	-29.5%
	5	+1.1%	+1.9%	+3.3%	+5.2%
	6	+3.0%	+6.6%	+10.5%	+17.2%
	7	+5.6%	+11.3%	+21.2%	+26.8%
	8	+9.3%	+18.7%	+28.5%	+42.8%
	9	+10.8%	+26.7%	+40.6%	+58.5%

Speed-Flow relationship

Figure 18 shows the example speed-flow relationship at 50% CAV fleet penetration for a variety of technical capabilities. The data is calculated as average vehicle speed as a function of flow, based on a 10 minute average.

Figure 18: Speed-flow relationship @ 50% penetration (Model A)

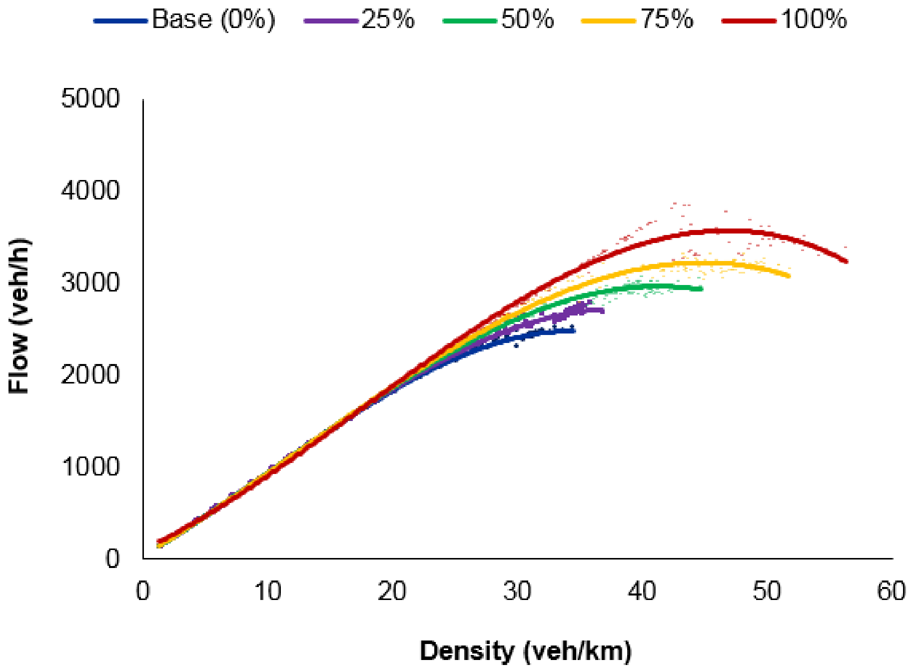


As would be expected, free-flow speed is maintained at low flow (<1000 veh/hour) for all scenarios. However, flow breakdown occurs much earlier for situations where there is a penetration of cautious CAVs.

Flow-Density relationship

The change in vehicle behaviour which allows greater road capacity is reduced longitudinal spacing. This is formalised as density – vehicles per unit distance. An example of this impact is shown in Figure 19. As with the speed-density relationship, each data point represents a 10-minute period. This shows varying levels of penetration for assertive CAV. The maximum achievable density – jam density, is higher with increasing penetration and increasing capability level, in line with expectations.

Figure 19: Flow-density relationship, Capability Level 8 (Model A)



3.3.2. Model B (multi-lane link)

Model B is a multi-lane link, with a single direction. Alongside longitudinal behaviour, vehicles are also free to choose lane; therefore lateral behaviour is also tested through overtaking manoeuvres.

Capacity

Table 10 shows the capacity impact when compared to the common base. Results are similar to those seen in Model A, with a decrease in capacity associated with cautious CAVs and an increase associated with assertive CAVs, and enlarged by increasing penetration rate.

Table 10: Model B capacity impact

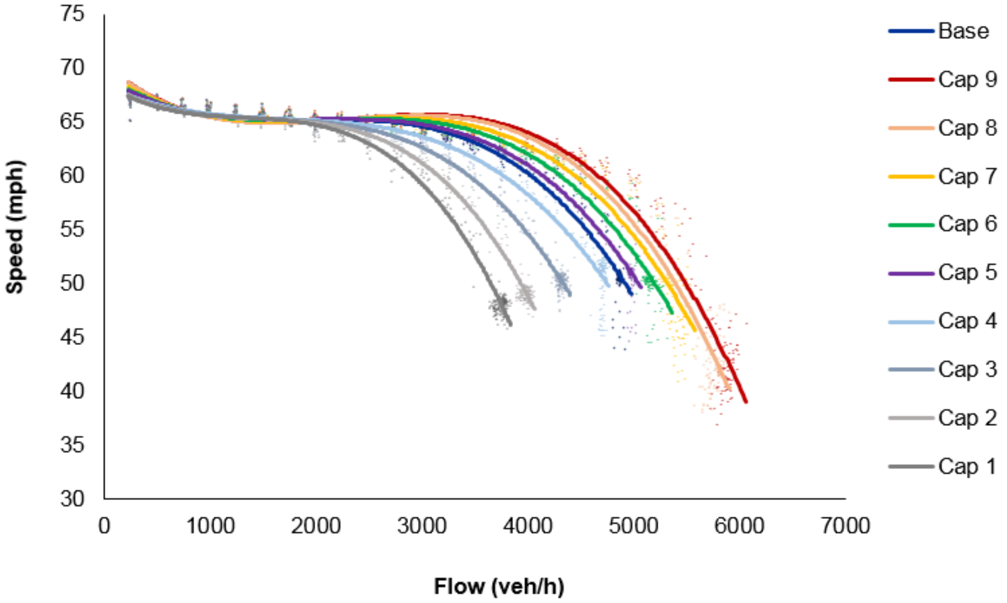
Percentage change from the base situation (0% CAV penetration)		**Penetration**			
		25%	**50%**	**75%**	**100%**
Capability	**1**	-11.7%	-22.6%	-31.6%	-38.3%
	2	-8.6%	-18.0%	-25.8%	-32.2%
	3	-4.1%	-11.2%	-17.3%	-22.7%
	4	-0.1%	-3.1%	-7.1%	-10.9%
	5	+1.0%	+2.2%	+3.5%	+5.5%
	6	+3.0%	+6.0%	+10.3%	+14.6%
	7	+5.4%	+10.6%	+17.9%	+25.1%
	8	+9.2%	+18.9%	+25.7%	+36.1%
	9	+10.8%	+20.4%	+29.9%	+44.1%

Speed-Flow relationship

Figure 20 shows the speed-flow relationship at 50% CAV penetration. The spread of data is apparent, particularly at higher levels of assertiveness. This is demonstrable of the variation that can be expected, particularly when combining longitudinal and lateral behaviours. Again, free-flow speed is maintained at higher flows with increased levels of CAV assertiveness.

As with Model A, improvements are not clearly shown until traffic demand reaches a certain level. This implies that the benefits of connected and autonomous vehicles will be more acutely visible in congested networks. The relationship also shows that with higher level of assertiveness, the network can accommodate a much higher level of demand, which is also demonstrated as increased capacity.

Figure 20: Speed-flow relationship @ 50% penetration (Model B)



3.3.3. Model C (signalised junction)

Model C is a signalised intersection common to urban areas. Regarding longitudinal behaviour, standstill distance (CC0) is a particularly important component of this model. The expectations are that CAVs will be stopped with reduced gaps in a queue. Furthermore, acceleration from a standstill is incorporated. The combination of these two parameters will impact the discharge possible from the stop line and hence the delay at the junction.

Capacity

Table 11 shows the capacity impact of the introduction of CAVs for this model. Again, greater benefits are associated with a high penetration of assertive CAVs, with an associated capacity reduction CAVs are setup to drive cautiously.

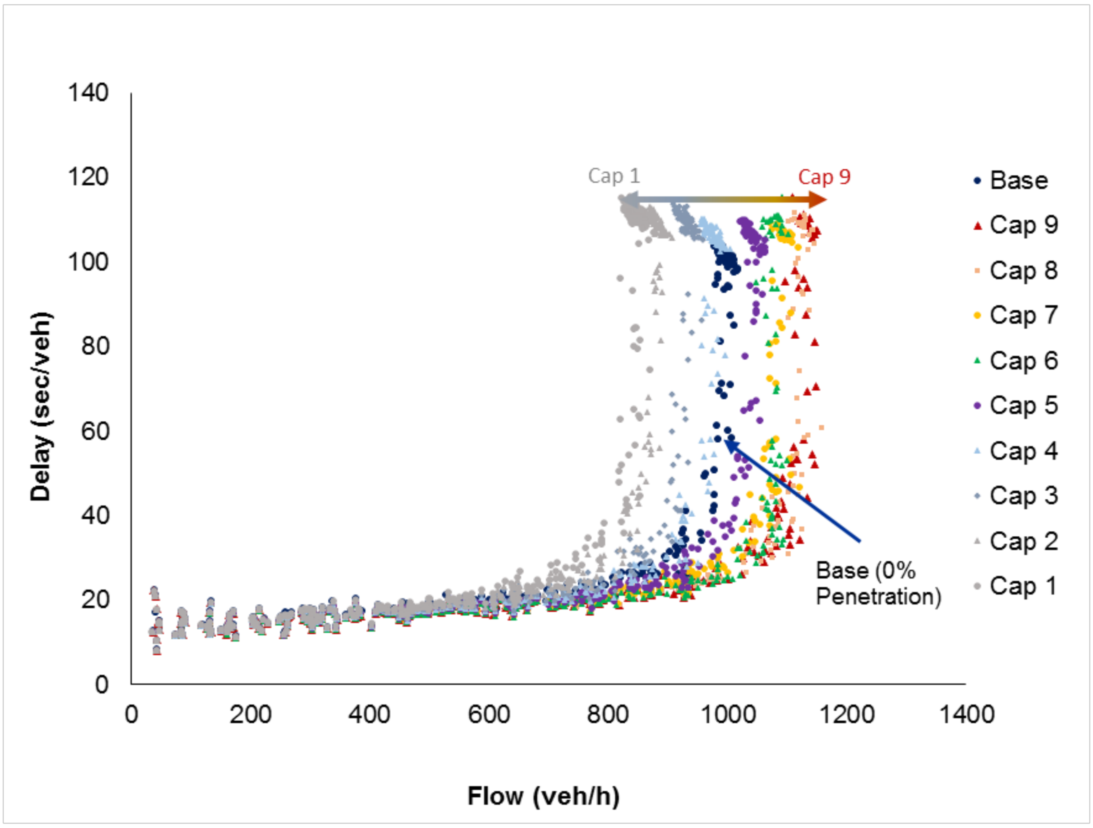
Table 11: Model C capacity impact

Percentage change from the base situation (0% CAV penetration)		**Penetration**			
		25%	**50%**	**75%**	**100%**
Capability	**1**	-9.2%	-15.3%	-20.9%	-24.9%
	2	-7.6%	-12.7%	-16.4%	-20.0%
	3	-3.8%	-7.1%	-9.1%	-11.0%
	4	-1.2%	-2.7%	-3.0%	-3.0%
	5	+2.2%	+4.1%	+6.7%	+10.4%
	6	+4.7%	+7.4%	+12.7%	+19.0%
	7	+4.4%	+9.0%	+14.8%	+25.0%
	8	+5.9%	+11.8%	+20.2%	+25.7%
	9	+5.6%	+13.0%	+19.7%	+25.0%

Delay

Figure 21 shows delay as a function of flow, at 50% penetration. For a given level of flow, delay is reduced for vehicles with a penetration of assertive CAVs. Delay is calculated as an average for all vehicles – therefore the benefits are not limited only to CAVs, but are fleet-wide. When vehicle flows are lower (such as in off-peak situations), there are no network wide delay benefits. This is sensible and expected.

Figure 21: Delay as a function of flow @ 50% penetration (Model C)



3.3.4. Model D (roundabout)

Model D is a roundabout with single approach and single circulatory lanes. Whilst longitudinal behaviour is a key feature of this model, gap acceptance is also considered.

Capacity

As the capacity measures the maximum attainable flow of the junction, gap acceptance is the deterministic factor in the number of vehicles that can enter the roundabout in high traffic volume. If CAVs are able to take smaller gaps when joining traffic streams, greater capacity will be realised. This is shown in Table 12.

Unlike Models A-C, some benefit is seen from the introduction of level 4 CAVs. These are described as being slightly more cautious than the legacy fleet in terms of following behaviour and gap acceptance. However, being CAVs, there is some improved behaviour in terms of throttle control (speed oscillation) and deceleration/acceleration behaviour. This is seen to outweigh the more cautious behaviour for this junction, in which conflicting movements must interact.

Table 12: Model D capacity impact

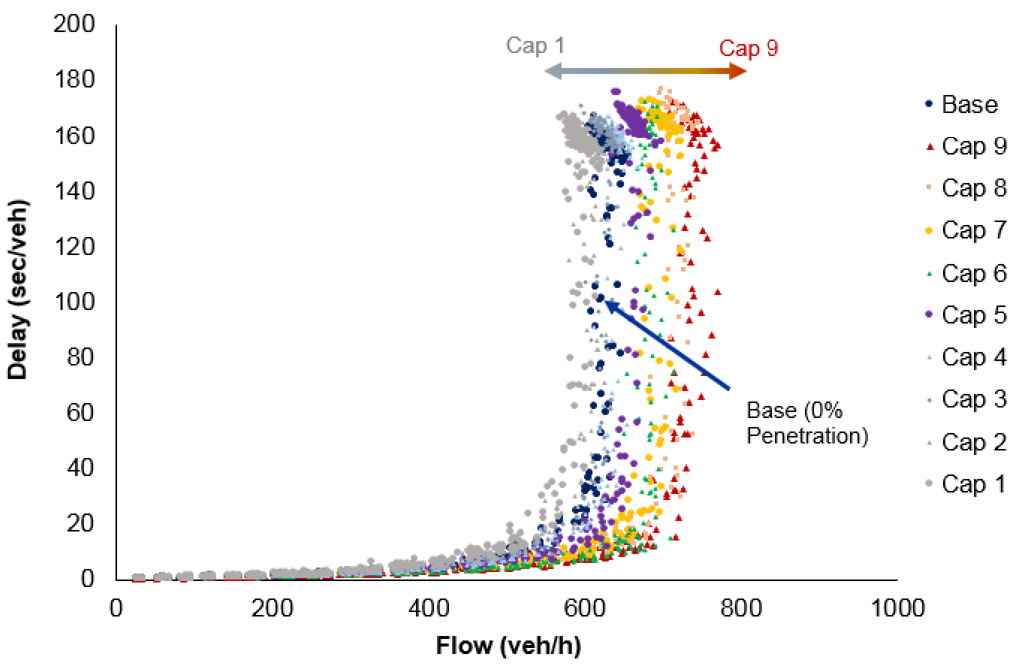
Percentage change from the base situation (0% CAV penetration)		**Penetration**			
		25%	**50%**	**75%**	**100%**
Capability	**1**	-1.6%	-4.9%	-7.4%	-10.8%
	2	-1.3%	-2.6%	-5.2%	-6.3%
	3	+0.7%	+0.0%	-1.1%	-2.1%
	4	+1.7%	+2.7%	+2.6%	+3.2%
	5	+3.6%	+6.0%	+8.0%	+11.2%
	6	+5.4%	+9.4%	+13.8%	+18.1%
	7	+6.0%	+12.5%	+18.6%	+23.9%
	8	+7.4%	+16.1%	+24.8%	+33.2%
	9	+9.1%	+18.4%	+31.4%	+42.5%

Results for Model D (a priority-type junction) demonstrate better performance than Model C (a signal controlled junction) results. This suggested the potential for differing levels of improvement depending on the infrastructure in question.

Delay

Figure 22 shows delay as a function of flow at 50% penetration for Model D. Results are similar to those shown for Model C. As only geometric delay is guaranteed at a roundabout, there is no impact at low levels of flow. Again, delay increases as a function of flow, with high penetrations of assertive CAVs resulting in higher capacity and lower network-wide delay.

Figure 22: Delay as a function of flow @ 50% penetration (Model D)



3.3.5. Model E (multi-lane link with merge)

Model E is a multi-lane link with merge, a common motorway or expressway situation in the UK. CAVs in this scenario will have changed longitudinal, lane-changing and gap acceptance behaviour.

Capacity

Figure 29 shows the headline results concerning the capacity impact of CAV introduction. Capacity in this model measures the maximum attainable flow passing the lane-drop section, and therefore represents the impact of gap acceptance at varying levels of capability.

Table 13: Model E capacity impact

Percentage change from the base situation (0% CAV penetration)		**Penetration**			
		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%

From the results table, benefits of a penetration of assertive CAVs are much greater than the disbenefits of a similar penetration of cautious CAVs. It is expected that when traffic in the mainline reaches capacity, cautious drivers will be unable to merge, compounding the effects.

Similarly to Model D, which considers gap acceptance in entering roundabout, improved CAV behaviour in throttle control outweighs some disbenefits from cautious behaviour, and Level 4 CAV scenario under penetration 50%, 75% and 100% still show a greater capacity than the base case.

Delay

Delay is also considered for vehicles at the point of merge in Model E, as shown in Figure 23 and Figure 24. This includes both the mainstream traffic and the vehicles waiting for merge on the leftmost lane.

Flow breakdown and subsequent delay occurs at higher levels of traffic demand for more assertive CAVs. The spread of data is particularly evidence in Figure 24.

Figure 23: Merge data collection (Model E)

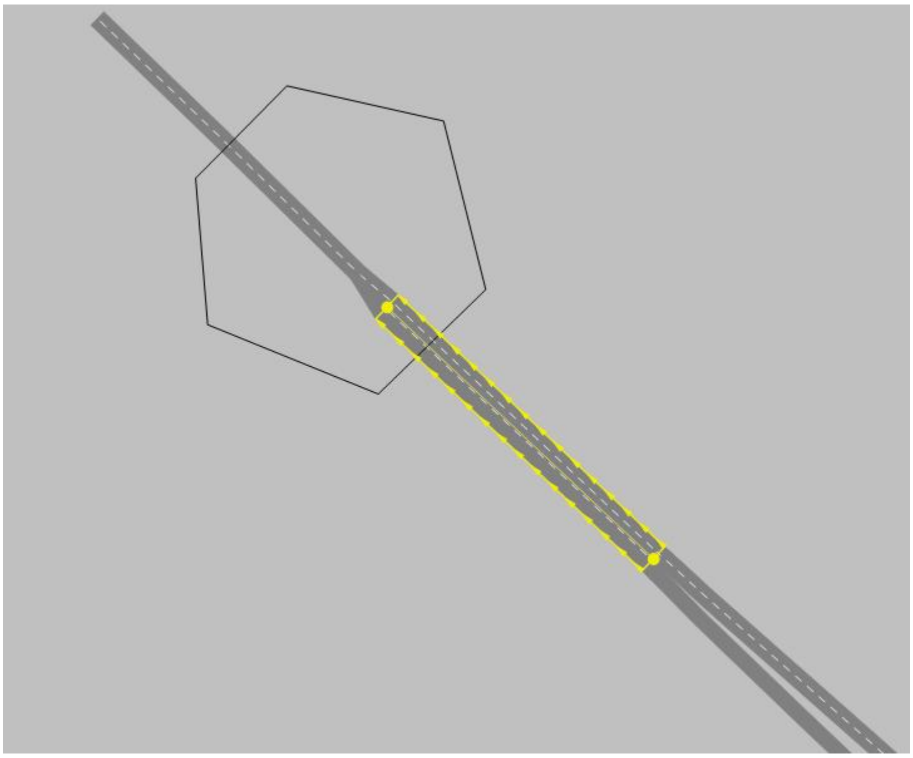
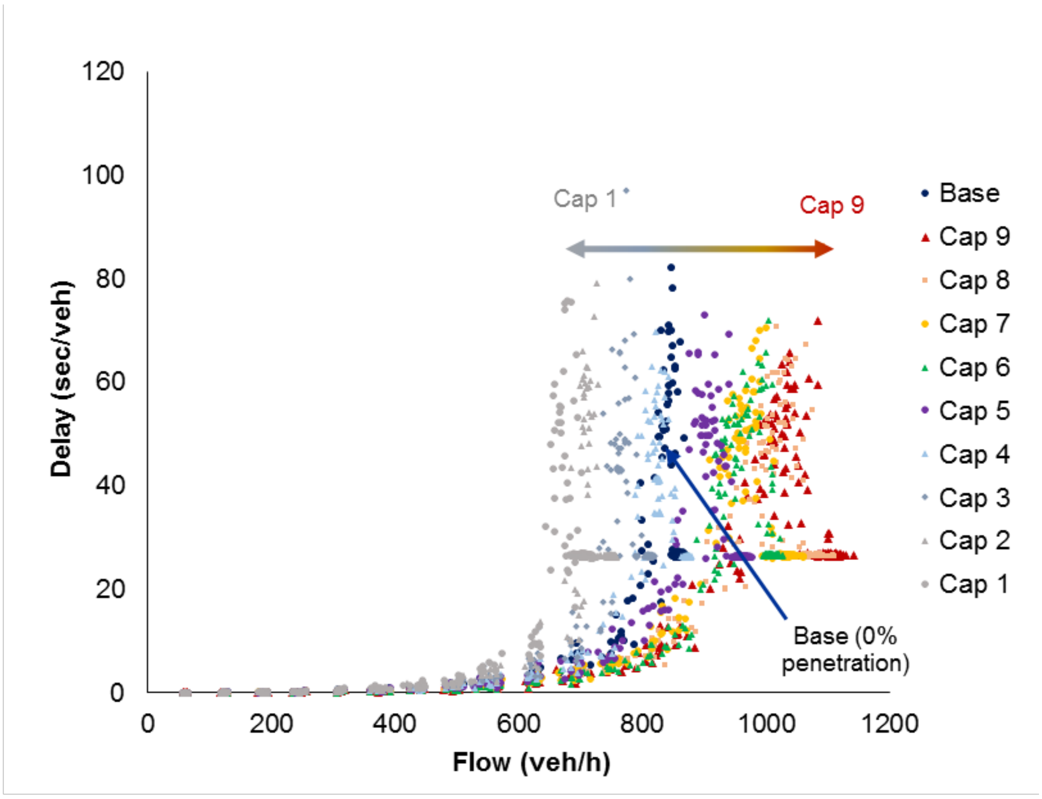


Figure 24: Delay as a function of flow @ 50% penetration (Model E)



Note that in Figure 24, there is a delay drop at the end of each capability level at around 26 sec/veh of delay. This is because when the flow on the mainline is reaching the maximum attainable flow, it becomes increasingly difficult for the vehicles on the leftmost lane to merge. Hence the vehicles passing the section are composed almost entirely by the vehicles originally on the mainline. This situation occurs in much higher demand levels in more assertive CAV scenarios, as can be seem from the more widely spread data points.

3.4. Simple model conclusions – CAV impacts

The simple models have been designed to isolate the impacts of particular behaviour changes in specific situations. Whilst they do not represent "real" situations, the results give an indication of the relative magnitude of capacity improvements that can be expected. Based on the results gathered (Section 3.3), this section draws out particular points of note.

The results are mostly intuitive

For the most part, the results are as expected. Enhanced capability of assertive CAVs, with smaller spacing and lower gap acceptance, allows greater road space utilisation, higher road capacity, lower delays and decreased journey times. More cautious CAVs, with higher spacing and less efficient utilisation of road space, do not aid measures of network performance.

Infrastructure must be designed and controlled to best serve the capabilities of the vehicle fleet

There are a number of instances where the results are not intuitive. In the case of Model C, the signalised intersection, levels 8 and 9 at penetration 75% and 100% do not follow the normal pattern. Given the sample of 10 random seeds, and the small difference between results, it is not possible to definitively state that capability 9 results in poorer performance than capability 8. There are however, some important points to note.

Model C consists of a signalised intersection. In order to maximise capacity in these situations, the traffic control system must be optimised to the particular characteristics of the flow. An example of this in a real-world setting is through sophisticated UTC systems, where signal timings are able to react to varying levels of demand. For these simple models, fixed signal timings have been set in order to exercise as much experimental control as possible. Therefore, without optimising[9] the traffic signals according to the traffic condition with CAVs, it might not be able to achieve the best junction performance. An important conclusion is that in order to maximise the capacity benefits potentially offered by CAVs, infrastructure, such as traffic control, must be in the right order.

The percentage improvements in the simple models vary. With gap acceptance taken into account, Model E has greater improvements compared to Model A and B, and Model D (roundabout) has more benefits than Model C (signalised junction). Priority-type junctions seem to be the network elements which will benefit particularly from enhanced vehicle behaviour; given these are often bottlenecks in congested situation, this is an expected result.

Smaller benefits in non-peak periods

Results graphs for speed-flow relationship, flow-density relationship, and delay as a function of flow have been plotted for certain simple models. The graphs demonstrate that the benefits are more apparent in high demand situations, while there is a much smaller network benefit when demand is lower. This is also an expected result, as the benefits are more expected to occur in congested traffic rather than free flow condition.

Choice is an important factor

It was assumed that CAV users are able to select certain aspects of driving behaviour to suit their own preferences. The simple model results shows that even though CAV automated functions are likely to have enhanced capability in throttle control, user choice in driving behaviour can make a significant difference in the road capacity and delay. Assertive CAVs are likely to result in increased performance of the network while cautious CAVs are likely result in reduced performance.

Regardless of the network situation, if CAVs adopt more cautious behaviour than the existing vehicle fleet – for example, driving at increased headways – the capacity of the road network is likely to be reduced. Even at low penetration (25%), ultra-cautious CAVs could result in a decrease in capacity of 10% for common highway situations (for example, Model E) while ultra-assertive CAVs could lead to an increase in capacity by 14%.

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[9] In this case, optimisation refers to the approximate mathematical optimisation of traffic signals to a defined parameter under a set of constraints

Penetration enlarges benefits/disbenefits from driving behaviour changes

Whether a CAV contributes positively or negatively to network performance is majorly determined by the scale of caution and assertiveness. The penetration rate appears a much larger determinant of the size of these benefits or disbenefits. Note that this is based on single CAV capability level in the fleet, and a mixture of CAV capability levels will be tested in complex models (Section 4).

Benefits are not symmetrical

The grading of capability levels (from 1 to 9) has been designed to represent the potential differences between cautious and assertive CAVs. As the capabilities are represented by a multitude of parameters (depending on the particular model), it is not appropriate to treat this as a linear scale (for example, capability 8 is not twice as assertive as capability 4). This is mainly because of the safety consideration of CAVs. However, there is a broad symmetry of the capabilities, as shown in Figure 16.

Scrutiny of the results suggests that the capacity benefits of assertive CAVs may be greater than the limitations of cautious CAVs. As these models do not investigate a mix of capabilities (other than CAVs and the legacy fleet), this will be a particular important aspect of the complex models (Section 4).

4. Complex models

The complex models have been designed to investigate the combination of particular behavioural changes on models representative to the UK road network. This chapters describes the construction of these models, definition of plausible future scenarios and results from the simulation model runs.

4.1. Complex model build

As introduced in Section 2.2.2, whilst the complex models are based on real-world situations, they have purposefully been built so as not to be site, time or purpose specific. Whilst they are consistent with key modelling guidelines and are demonstrably fit for the purposes of this work[10], they have not been subject to validation requirement as for scheme appraisal.

Two models have been developed, representative of the strategic road network (SRN) and an urban road network. The major network elements covered in these models is Table 14.

Table 14: Complex 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. Model F – SRN

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

An overview of the model is shown in Figure 25. The modelled network includes the following junctions:

1. A free-flow motorway to motorway interchange (Figure 26);
2. A partially signalised grade separated roundabout without grade separated through movements (Figure 27); and,
3. A fully signalised grade separated roundabout including grade separated through movements Figure 28).

The model also includes a section of dual carriageway A-road (expressway standard) and reduced speed dual carriageway approaches. It was decided to not include ghost island merge / diverge layouts as the route choice associated with this type of layout can be difficult to calibrate and is likely to add unnecessary complication to the operation of the model. As the key objective of this model is to consider the strategic road network more generally, assessing this style of layout is not felt to provide particular benefit.

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[10] For example, models utilise the more flexible Wiedemann 99 car-following model as opposed to the (often used) Wiedemann 74 model.

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 25: Overview of Model F, SRN, including major junctions

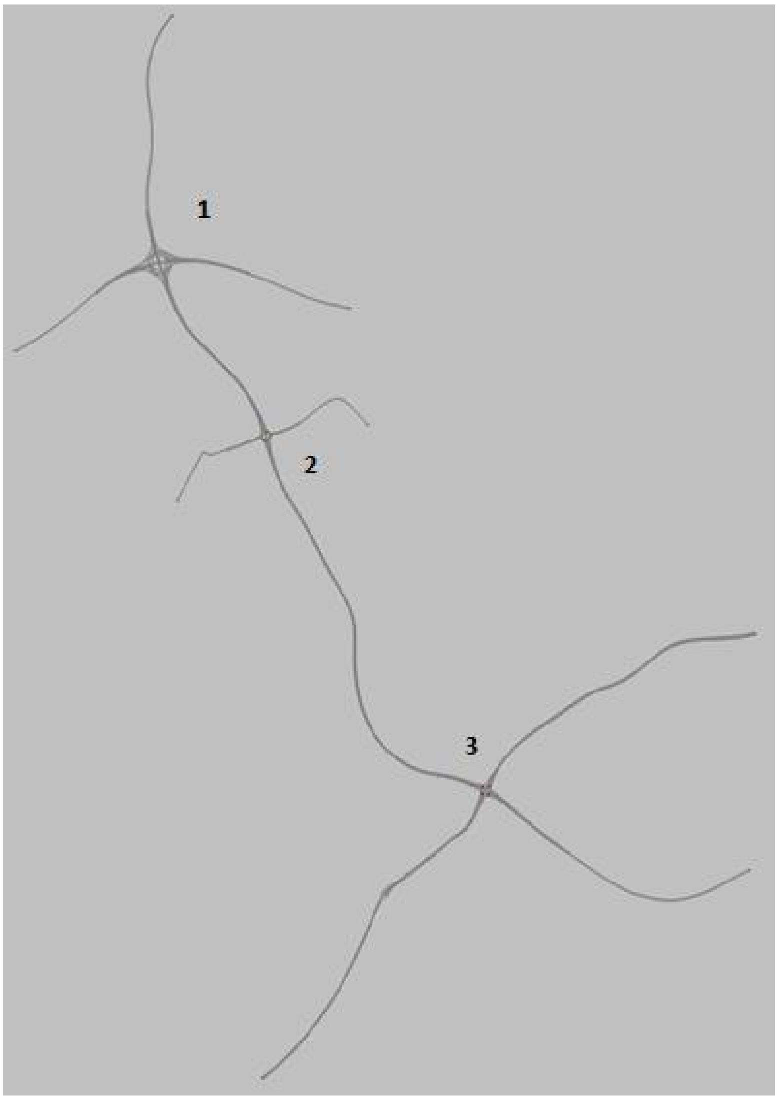


Figure 26: Free-flow interchange (Model F)

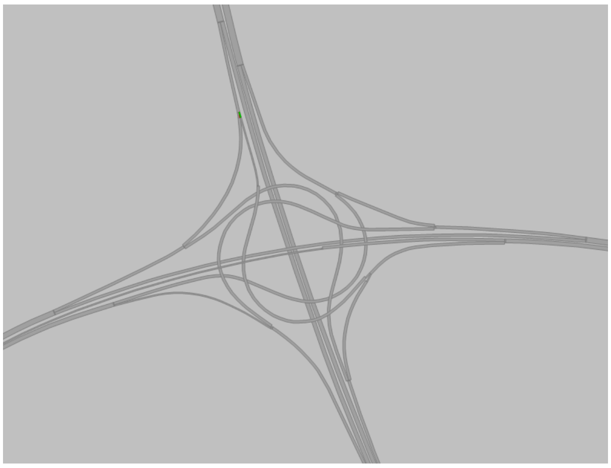


Figure 27: Partially signalised grade separated roundabout (Model F)

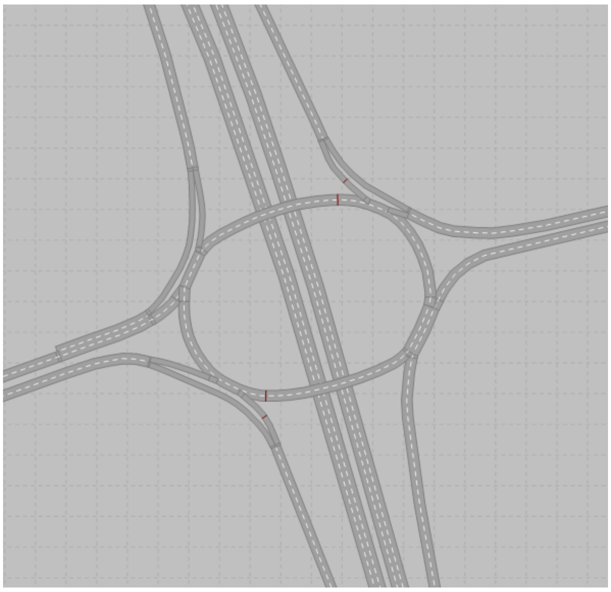
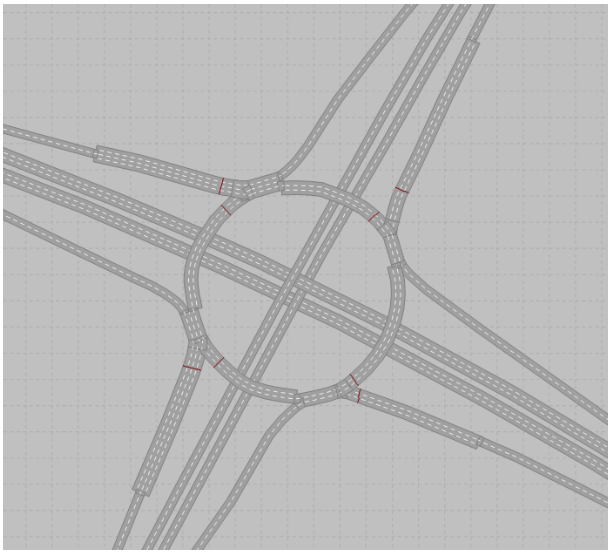


Figure 28: Fully signalised grade separated roundabout (Model F)



4.1.2. Model G – urban

Model G aims to capture the impacts of CAVs in an urban city network. It consists of typical urban network elements such as signalised junctions, pedestrian crossings and public transport infrastructure as described in Table 6. The model covers an approximate 3km stretch of urban A-road, including various side roads and intersections based on a real-world network[11]. 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 according to modelling guidelines to make sure the model is representative for the UK road network. An overview of the model is shown in Figure 29.

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[11] 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.

Figure 29: Overview of Model G, urban A-road

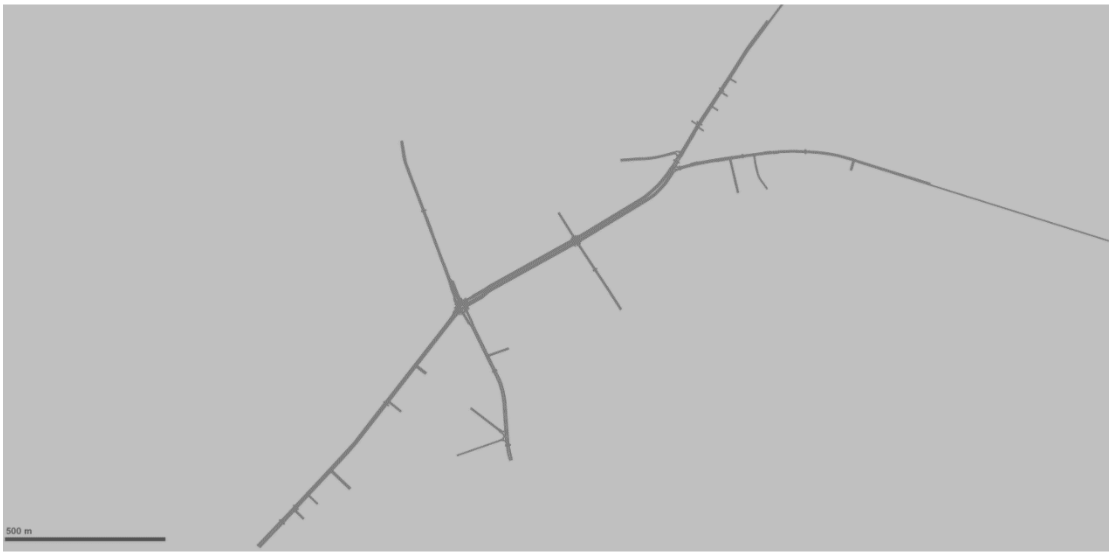
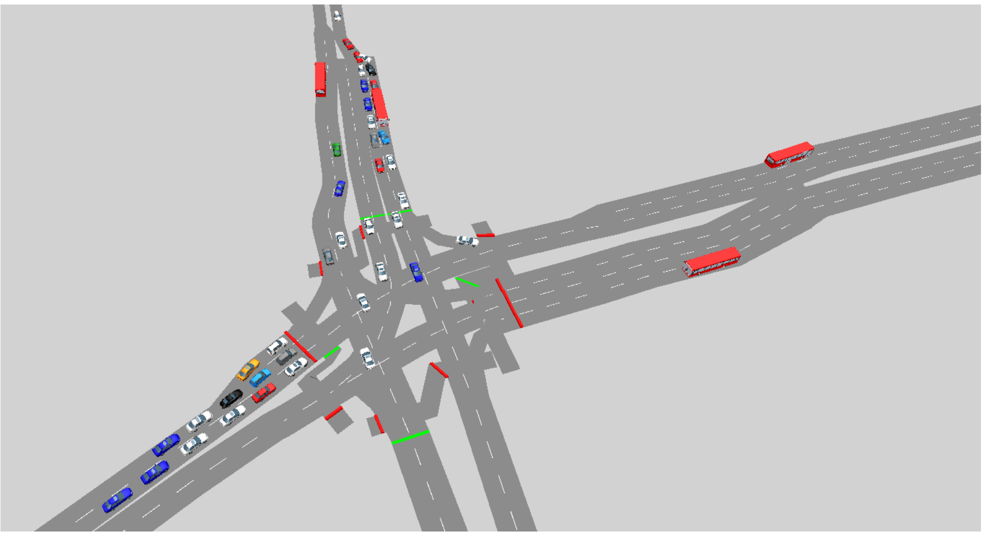


Figure 30 shows a detailed view of the central signalised intersection, showing various road geometries and stop line locations modelled. This includes pedestrian crossings and a dedicated bus lane.

Figure 30: Detailed view of Model G 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. Scenarios

The complex models described in the previous section are designed to investigate real-world situations relevant to the UK. As such, plausible scenarios for CAV introduction are required. This includes:

- A mix of different vehicle types;
- Deployment of different technologies and resulting capabilities;
- Realistic levels of traffic demand; and,
- Different traffic situations.

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, 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 traffic flow and 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 exists, consumer confidence will increase and better use of connected and automated technology will prevail.

4.2.1. CAV 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, these definitions do not necessarily map across to fundamental changes to the behaviour of the vehicle-driver unit – such as the levers discussed in Chapter 2 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 15 summarises these capabilities.

Table 15: Complex model capability levels

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. Whilst it is recognised that levels of driver assistance and autonomy exist in the current vehicle fleet, the base level of capability represents the default parameter set.

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. Stage 1 of this study highlighted the issues of user choice and comfort in evaluating traffic flow impacts of CAVs. For example, whilst the capability of CAVs may enable a shorter time gap, for reasons of comfort a user may choose a time gap longer than conventional vehicles. In the base models, this was represented as a scale of "cautious" and "assertive" drivers. In the application of complex models, a mix of cautious and assertive drivers are assumed.

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.

As mentioned at the start of this section, 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 – 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, complex model scenarios will be developed that involve the four different capability levels deployed on the network simultaneously.

To represent the capability of CAVs in the microsimulation model, driving behaviour parameters as described in Section 2 will also be modified for each capability level. Much of the functionality modelled in this work makes direct reference to autonomy of the vehicle. As discussed in Section 2, connectivity of the driver-vehicle unit is necessary to make the autonomous functionality possible in many of these cases, and is therefore implicit in the model environment.

However, as discussed in Section 2, it is not possible to capture some expected CAV features within the traditional microsimulation environment. One such capability is to dynamically alter behaviour – whether microscopic or macroscopic in nature. For example, a CAV may alter following behaviour depending upon the capability of the preceding vehicle, or make different routing decisions based on infrastructure alerts. This is an important aspect of connectivity. Logical rules for this behaviour, determined by the lead vehicle, are shown in Table 16.

Table 16: 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 complex models are described in detail in Appendix C of this report.

4.2.2. Fleet penetration

As discussed earlier, the complex models will consider a mixture of different vehicle capabilities deployed on the network at the same time. However, the basic approach to fleet penetration is the same as the simple models, with CAVs making up 0%, 25%, 50%, 75% and 100% of CAVs respectively. Within each penetration situation, the proportion of types of CAV, as described in Section 4.2.1, is varied. This is summarised in Table 17.

Table 17: 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%*
1	75%	25%	*20%*	*1.25%*	*1.25%*	*1.25%*	*1.25%*	*0%*
2	50%	50%	*35%*	*2.5%*	*2.5%*	*2.5%*	*2.5%*	*5%*
3	25%	75%	*50%*	*3.75%*	*3.75%*	*3.75%*	*3.75%*	*10%*
4	0%	100%	*40%*	*10%*	*10%*	*10%*	*10%*	*20%*
5	0%	100%	*0%*	*0%*	*0%*	*0%*	*0%*	*100%*

The fifth scenario represents a theoretical upper bound, where all vehicles on the road are fully automated CAVs. The CAV penetration is applied equally to all parts of the vehicle fleet – passenger cars and goods vehicles.

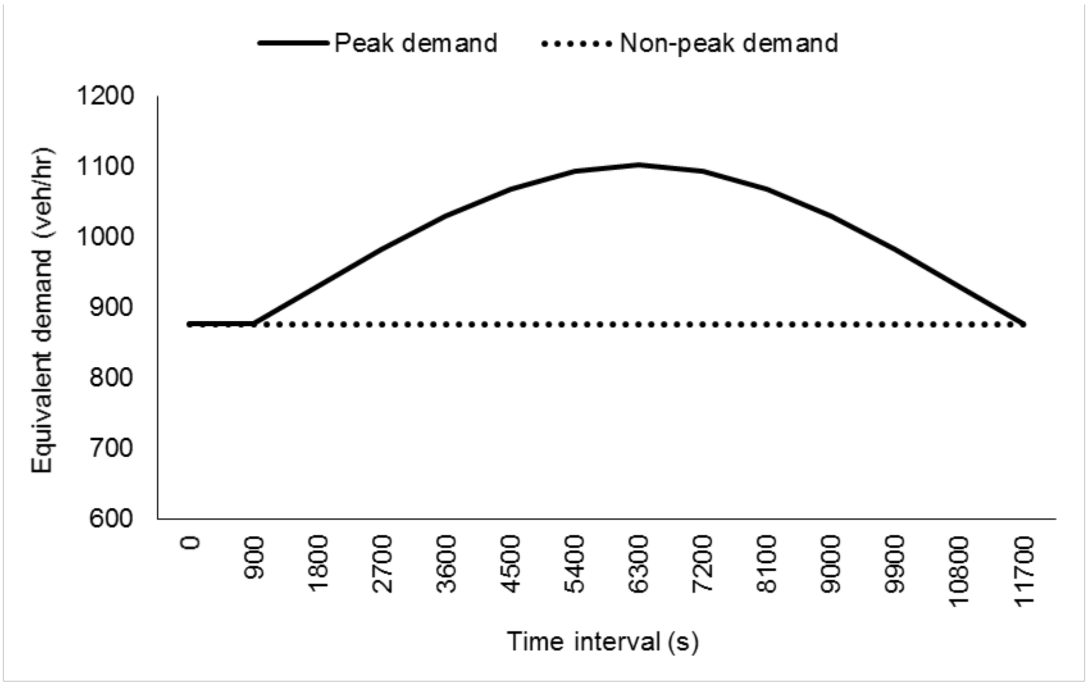
4.2.3. Traffic demand

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 variable demand, reflecting that observed in the AM peak generally. An example for Model G is shown Figure 31.

Figure 31: Model G – demand profile



The complex nature of these networks, coupled with the application of a standard demand scenario, makes calculation of single value of "capacity" difficult and potentially misleading. More appropriate measures of network performance are discussed in Section 4.3. Evaluation of capacity for specific traffic situations are discussed in Chapter 3.

As discussed in Chapter 2, 10 random seeds will be used for each scenario, giving a range of results and representing the stochastic nature of traffic flow and demand.

4.2.4. HGV-only case

Barriers to entry of connected and autonomous technology, particularly of a higher level, may be such that it is only attractive to commercial fleet operators. A specific scenario has been developed to consider HGVs only.

The scenario has been applied to the SRN network only, as HGVs are a more significant part of this model. Results will focus on the network performance and travel time differences for both passenger cars and HGVs to investigate the potential impacts and benefits.

4.3. Complex model results

This section provides the results obtained from both complex models. Explanation and discussion are also given. Additional results can be found in Appendix E of this report. Results here apply to all vehicles – the legacy fleet and CAVs (both passenger cars and goods vehicles) – unless otherwise stated.

The results for each complex model focus 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.

The results have been generated in a similar fashion to the simple models (Section 3). Best-fit curves have been generated for each situation, with R-squared values scrutinised for appropriateness. It is noted that the range of observed data is much higher than those of the simple models; this is attributed to the greater complexities of the modelled scenario.

4.3.1. SRN model results

Model F is relevant to the strategic road network, considering motorway and A-roads, with common junction, merge and diverge arrangements. The network was previously described in Section 4.1.1, and the modelled scenarios in Section 4.2.2.

Network performance

Figure 32 shows the progression of delay with modelled time. As discussed in Section 4.2.3 (and demonstrated in Figure 31), demand for the complex models is increased over the course of the simulation, in line with the expectations of a peak period. As such, congestion is also expected to increase, with associated delay to vehicles. Traffic flow then decreases at the end of the period, with congestion and delay dropping. The upper bound represents 100% penetration of Level IV CAVs.

The x-axis, modelled time, represents a series of discrete, sequential time periods for which network performance is assessed. In this case, each point represents a 15-minute period. As the demand profile follows a normal distribution, the average network delay increases with time in each scenario, and then decreases as congestion is alleviated.

Delay increases in this way over the course of the model for all scenarios. However, for high levels of CAV penetration, there is a much smaller increase in delay and the network recovers more quickly to an uncongested state.

The scenarios of 25% and 50% CAV penetration do not demonstrate much improvement over the base case. In this instance, 25% penetration potentially induces more delay. This is the result of the deployment of cautious CAVs, whilst assertive CAVs are limited by the legacy fleet. This is a key result – early CAVs may be constrained in performance by the limitations of the existing, legacy fleet.

Figure 32: Model F network delay by simulation time (peak period)

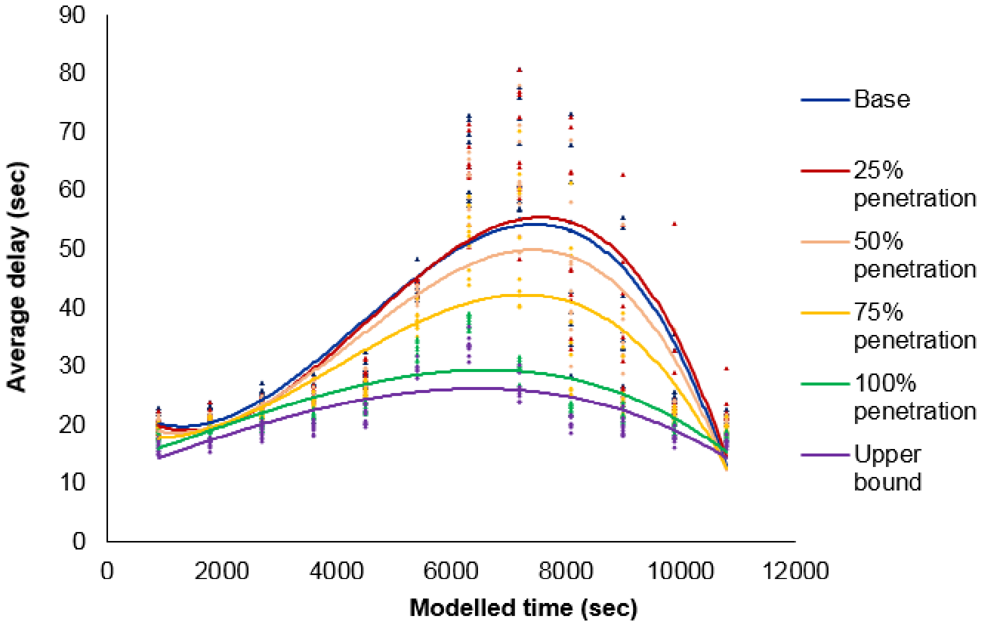


Figure 33 shows network delay over the entire modelled time period. This suggests a higher penetration of CAVs, especially with more fully automated and ‘assertive’ CAVs in the vehicle fleet is required before network delay benefits are achieved.

Figure 33: Model F network delay (peak period)

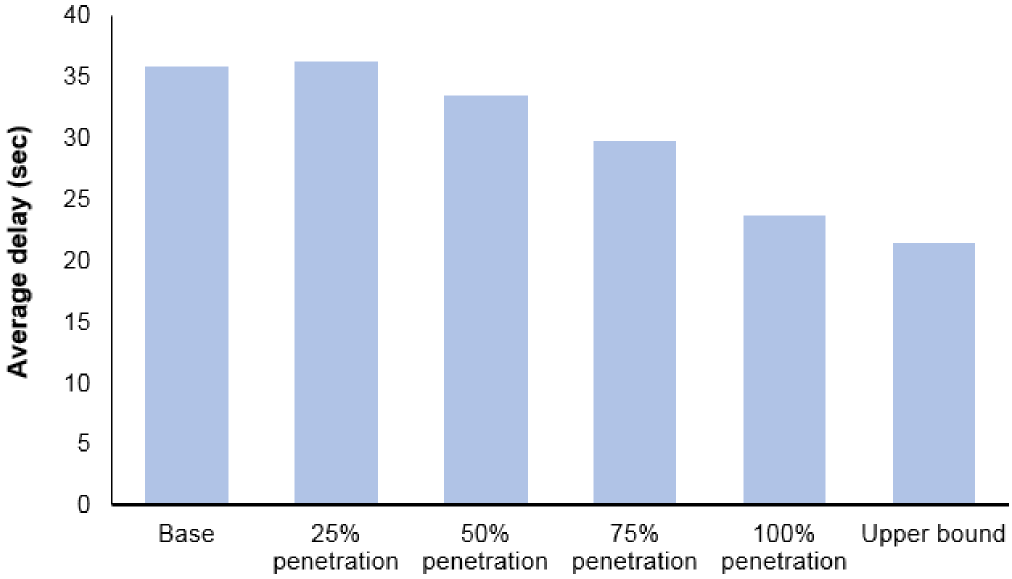


Figure 34 shows average network delay for the low-demand situation. In general, delay is much lower in this period as expected. Benefits as a result of CAV implementation continue to increase with penetration rate due to more ‘assertive’ CAVs in the fleet.

Figure 34: Model F network delay (non-peak period)

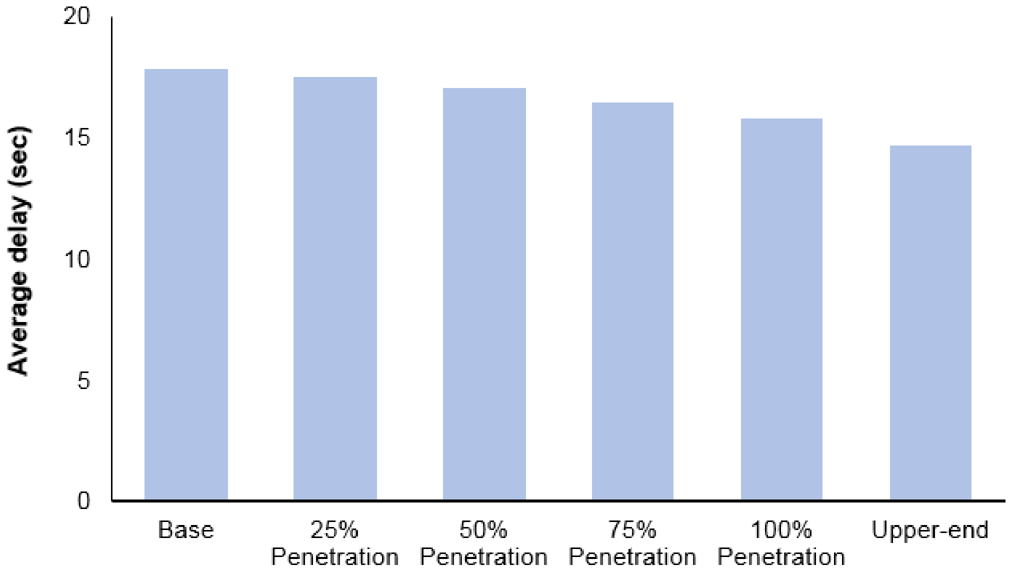
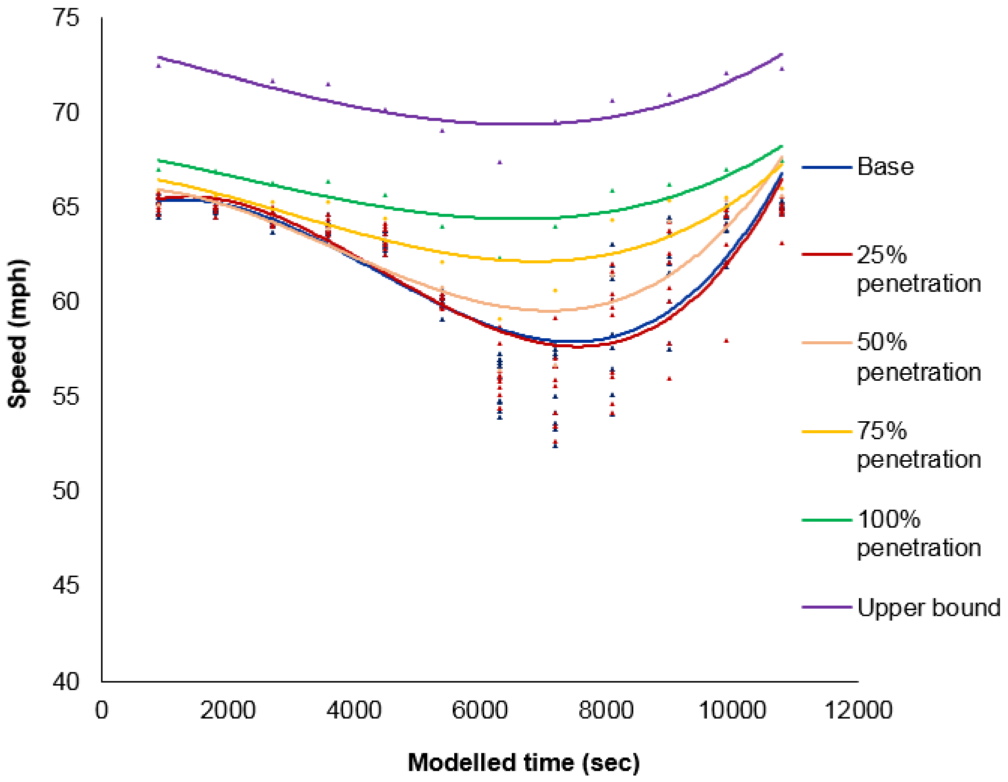


Figure 35 shows network average speed. Higher speeds are maintained with a high penetration of CAVs. This is supported by journey time data discussed later in this section. As with delay based results, there are disbenefits at the 25% penetration level due to the presence of 'cautious' CAVs and the limiting factor of the legacy fleet.

Figure 35: Model F network average speed (peak period)



Junction performance

Due to the large size of the network, particular points have been selected for data collection. These are shown in Figure 36, Figure 37 and Figure 38, and refer to the junctions previously numbered in Figure 25.

Figure 36: Model F data collection (junction 1)

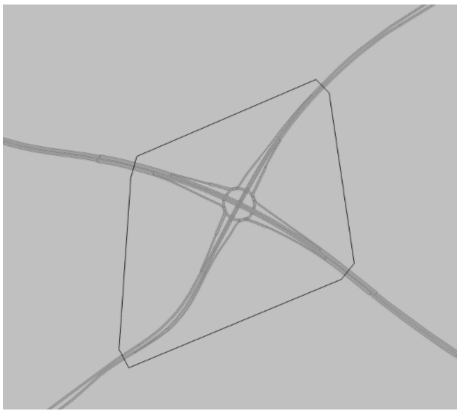


Figure 37: Model F data collection (junction 2)

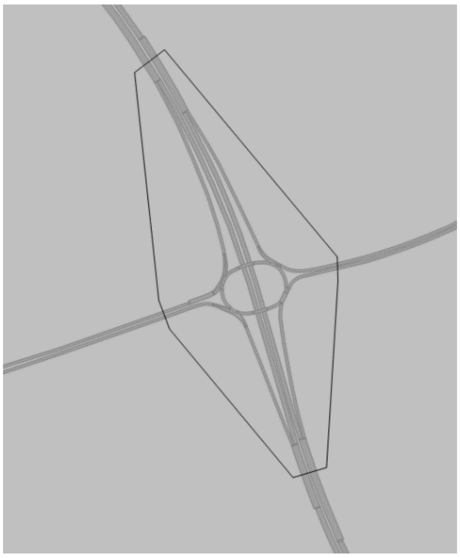


Figure 38: Model F data collection (junction 3)

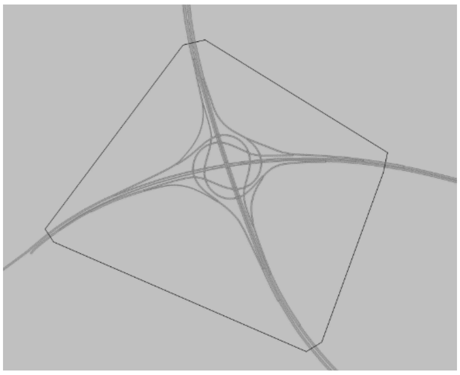


Figure 39 shows the improvement in delay for each junction as a result of increasing CAV deployment. The largest improvements are seen at the free-flow interchange. This is potentially a result of the larger influence of changed following behaviour in this type of interchange, and the higher speeds that can be maintained.

It should also be noted that the modelled traffic signals have not been altered in the future scenarios, so may not reflect the most appropriate configuration for the traffic present. As expected, much lower relative benefits are seen in the low demand situation, as shown in Figure 40.

Figure 39: Model F average junction delay (peak period)

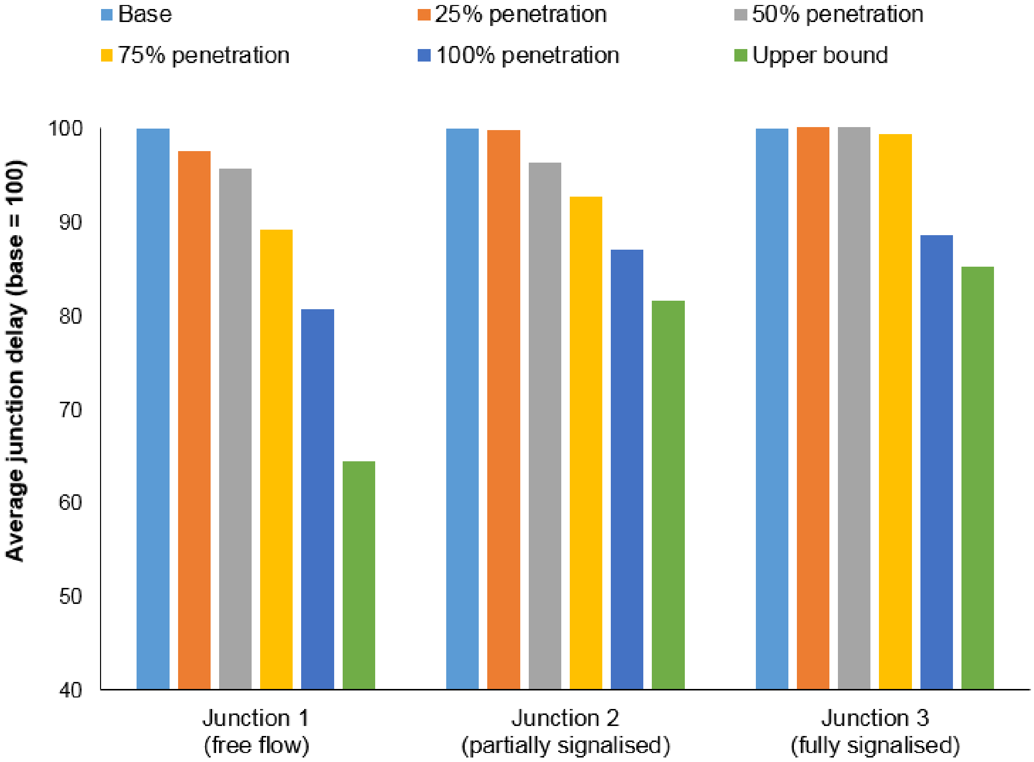
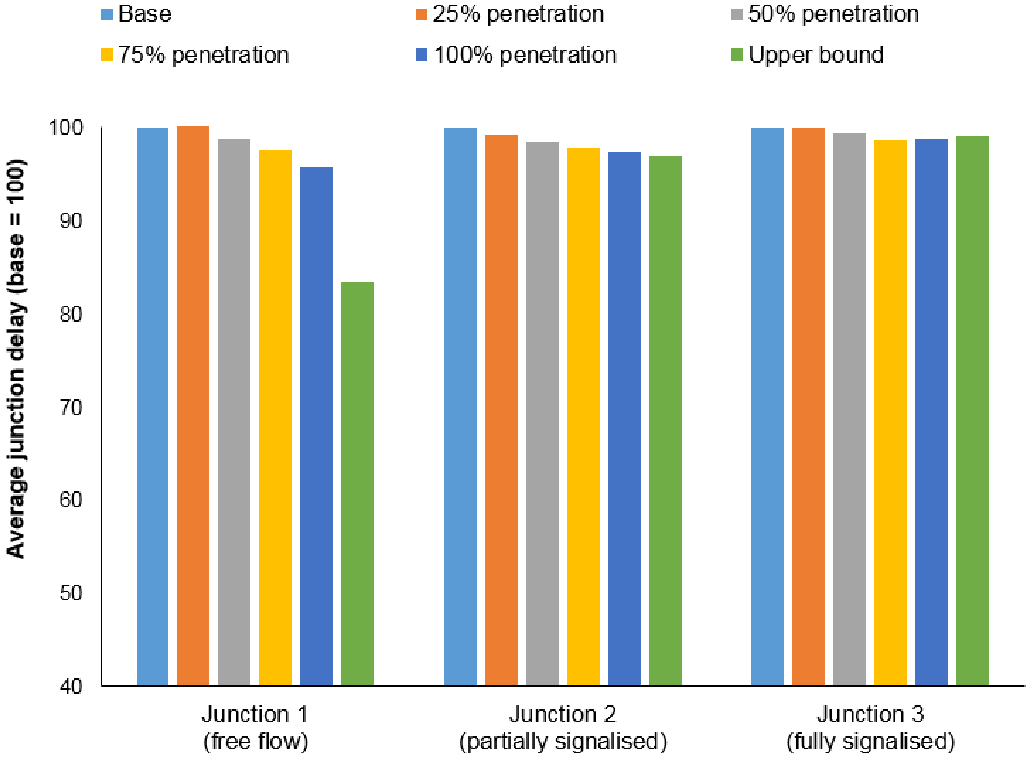


Figure 40: Model F average junction delay (non-peak period)



Travel time

Particular routes have been considered in order to assess the impact on journey times. These are shown in Figure 41.

Figure 41: Model F journey time segments

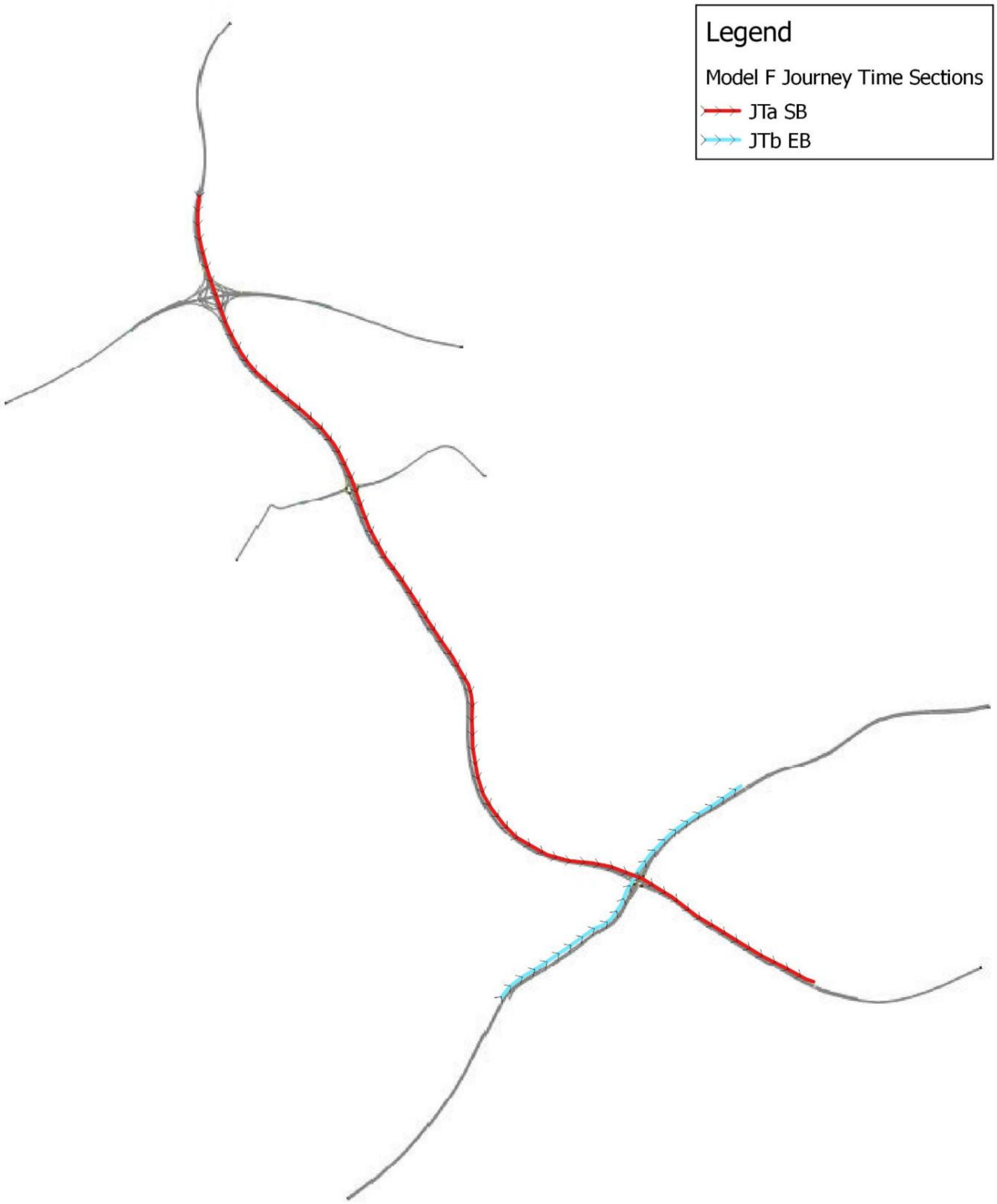
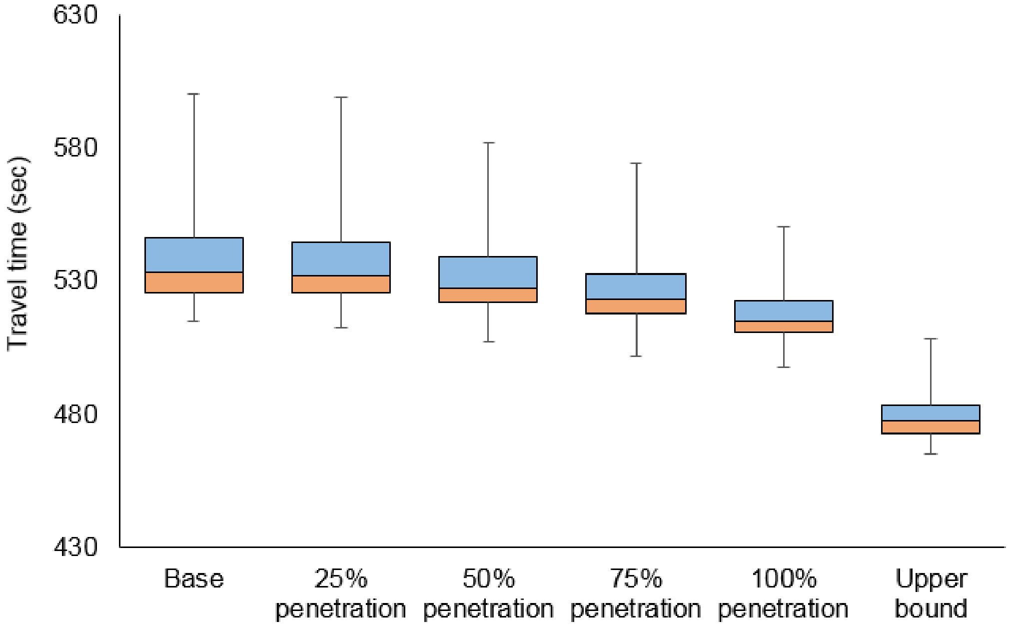


Figure 42 shows the range of peak-period journey times exhibited on segment *JTa*. There is a clear improvement in journey times with increasing penetration of CAVs for the vehicles on this segment, especially with more assertive CAVs at the improved level of capability. The constrained range of data also suggests improved journey time reliability in successive scenarios.

Figure 42: Model F journey times (segment JTa) peak period



For segment *JTb*, improvements are not clearly achieved until 75% penetration where there are much higher number of 'non-cautious' CAV in the fleet, as shown in Figure 43. Note that the only junction on the route of *JTb* is a fully signalised junction which has not been subject to signal time optimisation in future years. This suggests that the infrastructure changes (e.g. traffic signals) may be an important factor in realising the potential benefits of CAVs.

Figure 43: Model F journey times (segment JTb) peak period

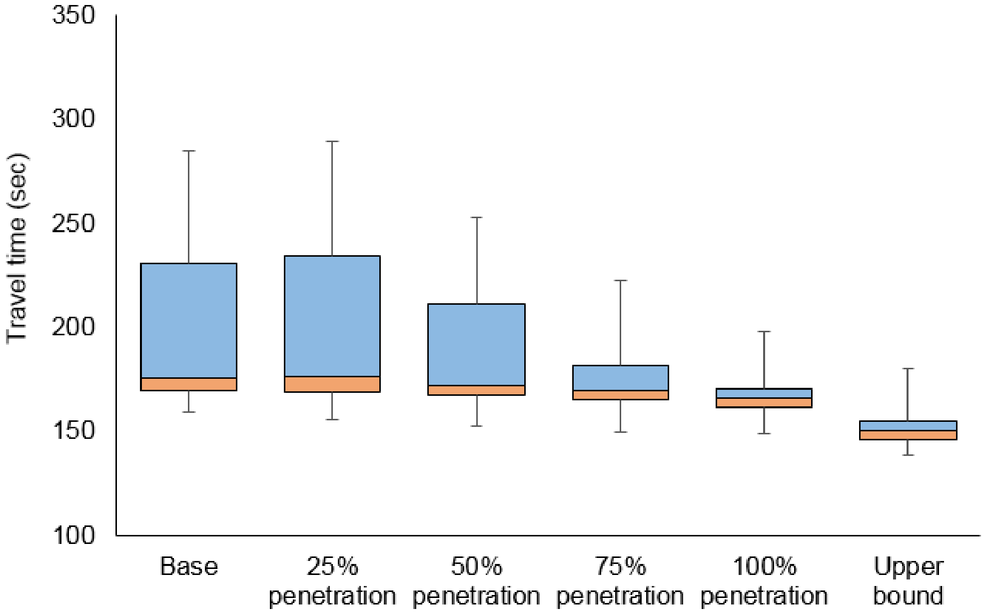


Figure 44 shows average journey time, split by scenario and according to fleet type (legacy fleet and CAV). This incorporates all vehicle classes (passenger cars and goods vehicles). Whilst CAVs generally experience greater benefits, journey time improvements are experienced on a network-wide level.

Figure 44: Model F journey time (segment JTa) peak period by vehicle type

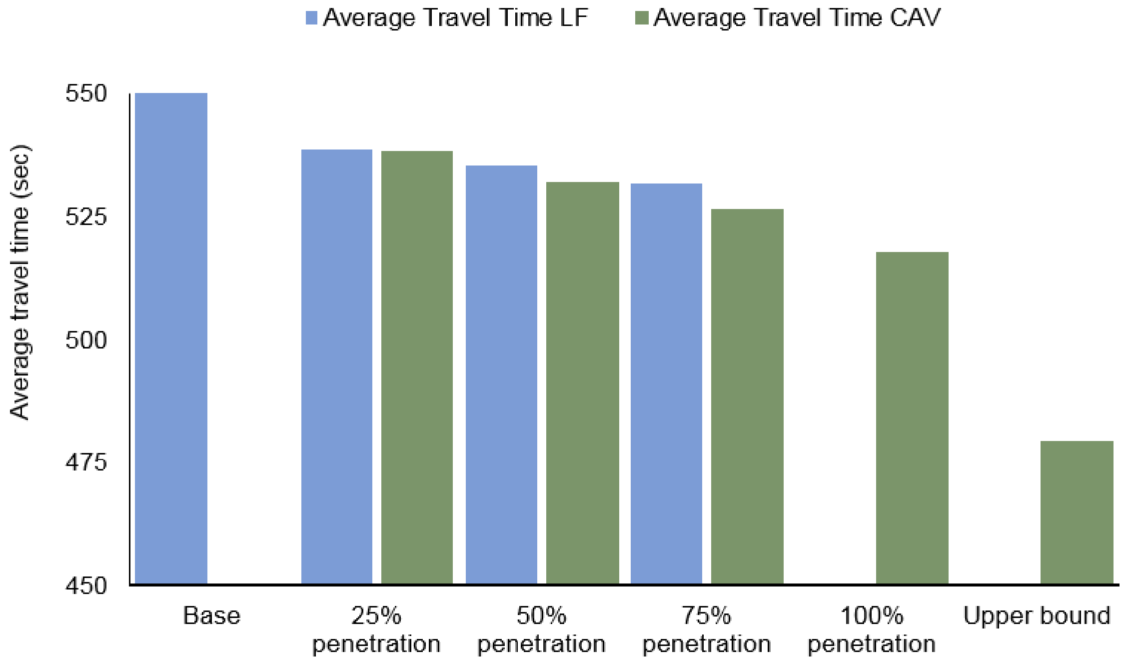


Table 18 and Table 19 summarise journey time results for each segment. Improvements are seen for both CAVs and the legacy fleet. However, in general, CAVs experience greater benefits.

Table 18: Journey time summary – 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	42,203
25%	538.5	599.5	19.4	42,296
50%	533.6	581.9	17.7	42,137
75%	527.7	574.2	15.3	42,039
100%	517.8	550.4	10.5	42,160
Upper bound	479.3	508.4	9.1	42,269
Legacy fleet				
Base	539.8	600.6	20.2	42,203
25%	538.6	601.1	19.6	31,648
50%	535.4	581.6	17.5	21,152
75%	531.7	581.9	16.3	10,610
100%	-	-	-	-
Upper bound	-	-	-	-
CAVs				
Base	-	-	-	-
25%	538.4	598.4	20.5	10,548
50%	531.9	583.7	18.8	20,814
75%	526.4	571.8	15.7	31,074
100%	517.8	550.4	10.5	40,960
Upper bound	479.3	508.4	9.1	42,269

Table 19: Journey time summary – 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	53,090
25%	207.1	343.8	55.8	53,052
50%	198.9	345.1	51.4	53,055
75%	187.2	355.1	42.9	53,091
100%	166.6	180.4	6.0	53,060
Upper bound	151.5	173.6	6.7	53051
Legacy fleet				
Base	202.8	317.4	50.3	53,090
25%	207.4	345.3	56.1	39,765
50%	199.8	344.5	51.8	26,614
75%	188.6	364.0	43.6	13,365
100%	-	-	-	-
Upper bound	-	-	-	-
CAVs				
Base	-	-	-	-
25%	206.1	339.0	55.1	13,178
50%	198.1	345.8	51.0	26,143
75%	186.7	353.3	42.6	39,267
100%	166.6	180.4	6.0	51,533
Upper bound	151.5	173.6	6.7	53,051

HGV-only case

The HGV-only case investigates the impacts of applying connected and autonomous vehicle technology to HGV only, rather than the entire vehicle fleet. However, the scenarios are as described in Section 4.2. Impacts to both network benefits and individual vehicle types are shown and discussed.

Average network delay for the HGV-only case at each penetration level is shown in Figure 45. The benefits are not clearly achieved until the upper bound scenario with 100% assertive CAV HGVs. As HGVs are a small proportion of the total vehicle fleet (approximately 14% in the testbed SRN model) of the SRN model, low penetrations of CAVs within this are unlikely to yield significant benefits. At the upper bound, all HGVs are assertive CAVs. However, in this situation they are still limited by the behaviour of the existing legacy fleet.

Figure 45: Model F HGV-only case network delay by simulation time (peak period)

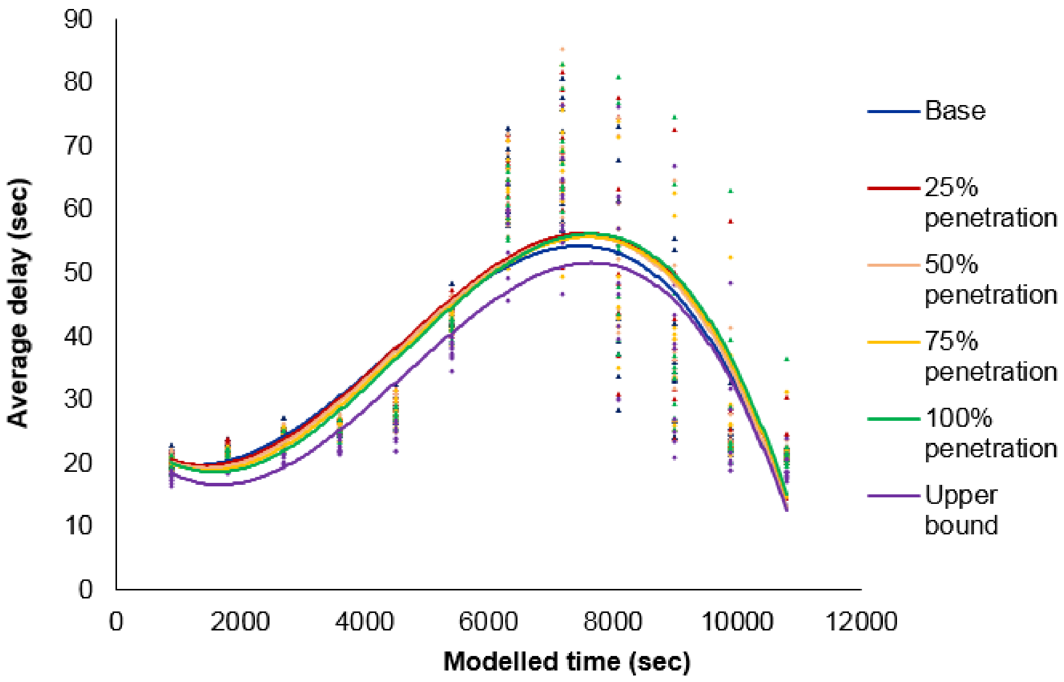
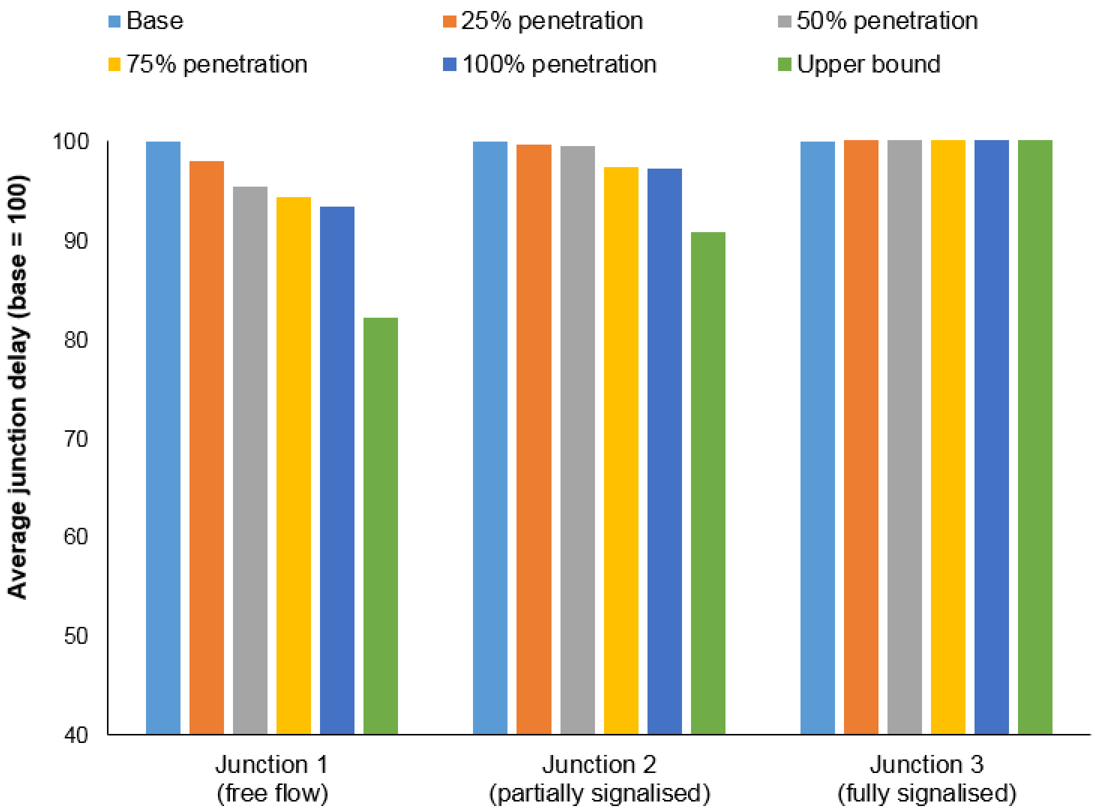


Figure 46: Model F HGV-Only case average junction delay (peak period)



Junction performance of the HGV-Only case is shown in Figure 46. The results are similar to those seen in the previous set SRN model scenarios. Again, greatest benefits are gained at junction 1, where the potential for improvements for fast flowing, closely spaced traffic are highest.

Figure 47: Model F HGV-Only case journey time (segment JTa) peak period by vehicle type

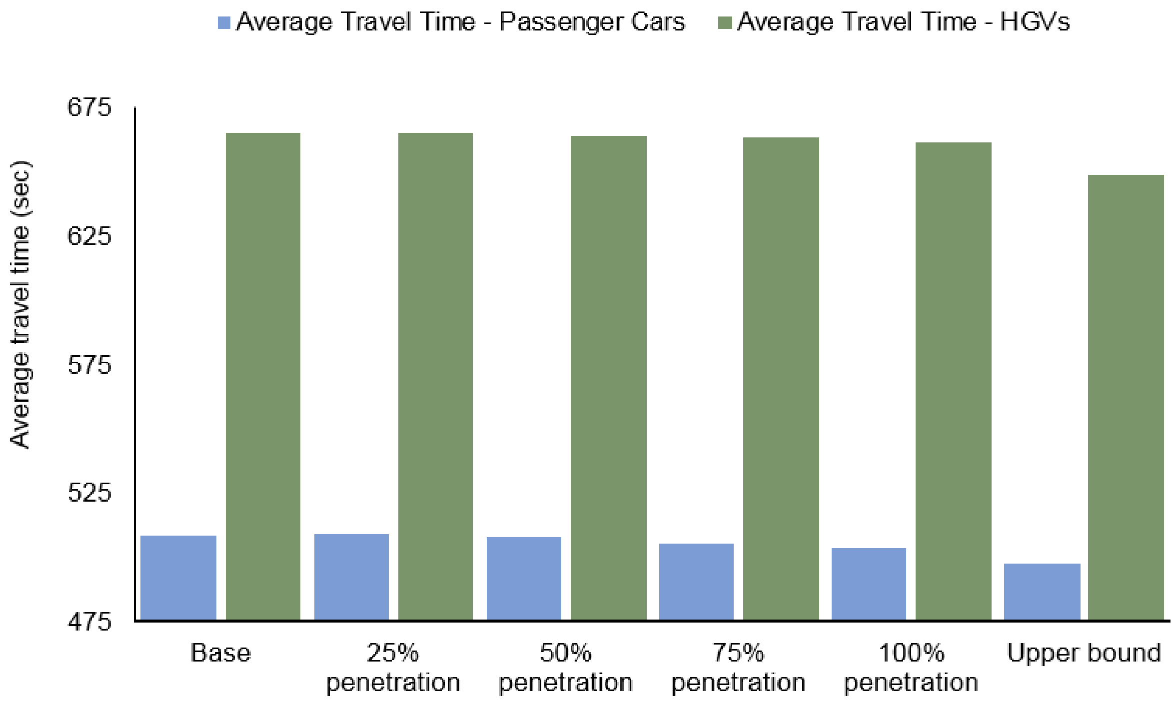
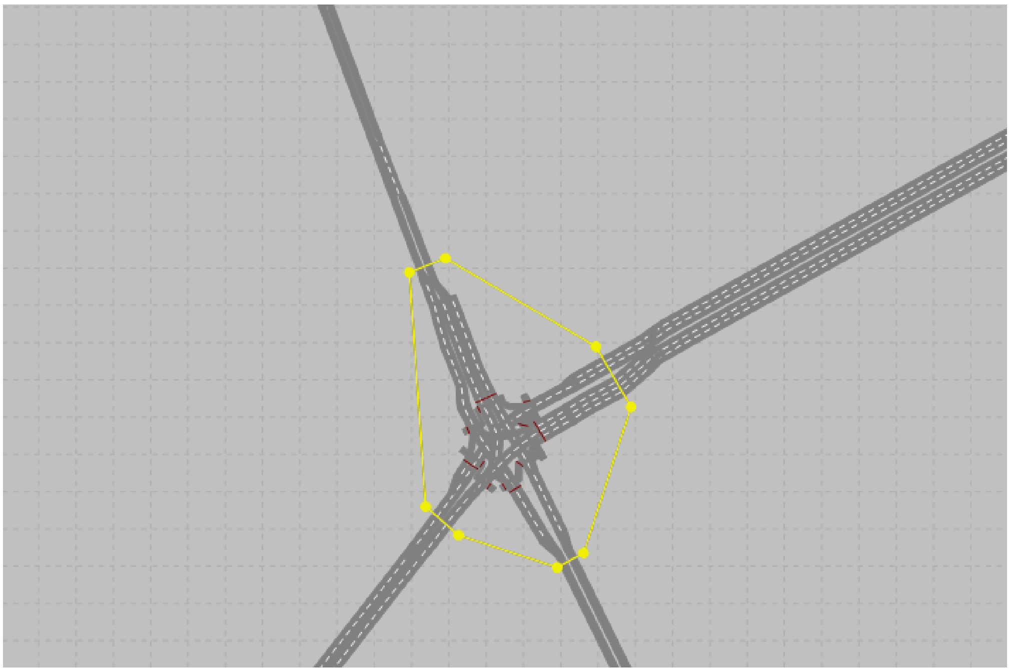


Figure 47 shows the average journey time by vehicle type for segment *JTa*. Improvements are shared across the fleet, but are relatively small. As with previous results, benefits are likely to be smaller due to the limitations of the existing vehicle fleet.

4.3.2. Urban model results

Model G is relevant to urban A roads, featuring signalised junctions, pedestrian crossings and dedicated PT infrastructure. In addition to network performance, journey times were considered for the main through route. In addition, data collection specific to the central signalised junction has been carried out, as shown in Figure 48.

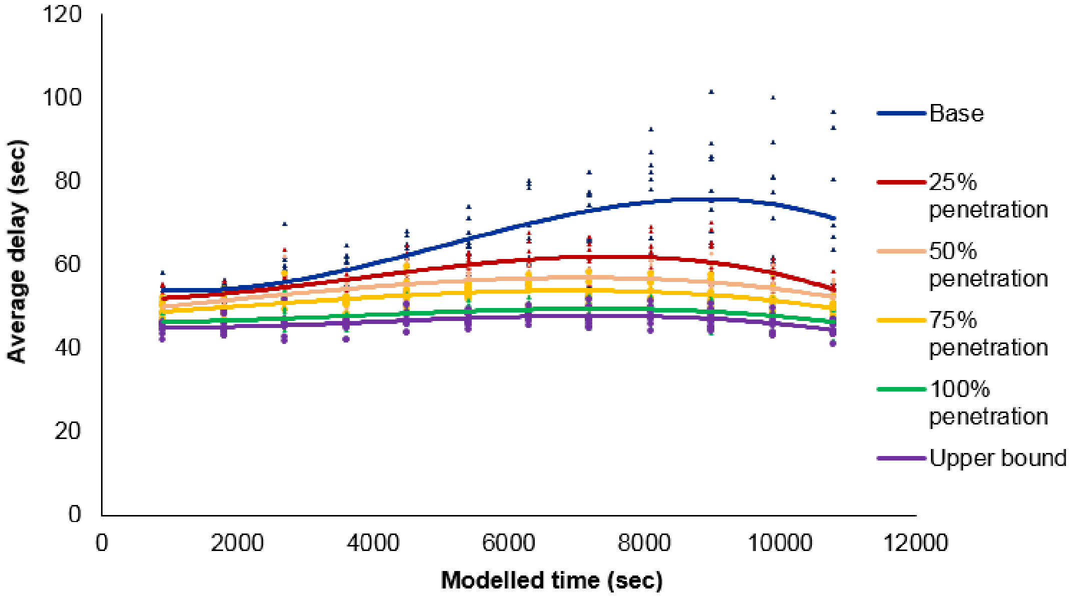
Figure 48: Model G data collection node (signalised junction)



Network performance

Figure 49 shows network delay as a function of simulation time, with each data point representing a 15-minute (900 second) period. As with Model F, demand increases in common with a normal peak period. There is a marked improvement with increasing CAV deployment, with congestion significantly reduced with higher penetrations. Similar to Model F, the network is able to recover faster from recurrent congestion at higher penetration levels.

Figure 49: Model G network delay by simulation time (peak period)



In comparison with the SRN model, greater benefits are seen at the lower levels of penetration (<75%). 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 and better maintenance of speed. This helps in harmonising traffic flow, and cutting out a substantial proportion of speed variation.

Furthermore, it is expected that there are more conflicting lateral movements in the urban model than the SRN model. These are controlled to an extent by the gap acceptance criteria, modification of which was shown to have greater potential benefits in simple models D and E.

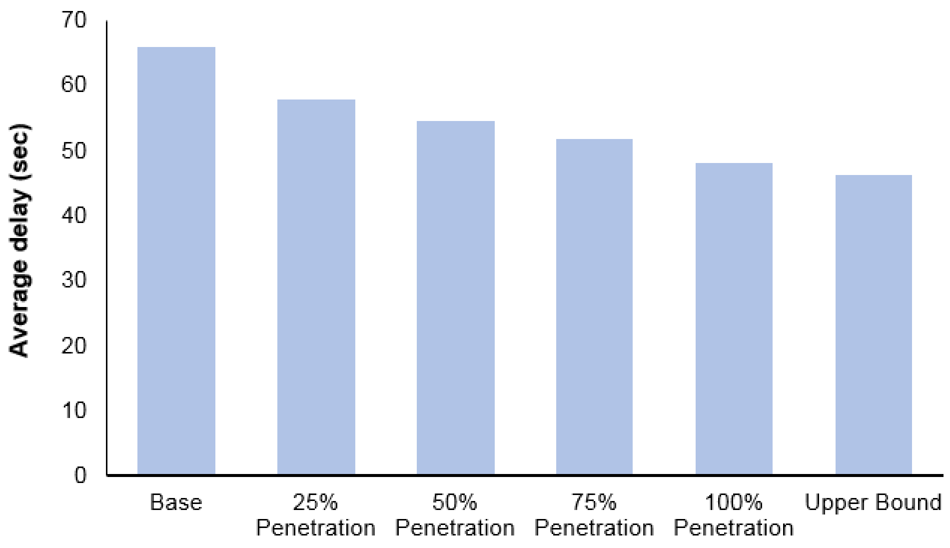
In summary, the greater relative benefits of low penetration in urban situations is attributed to:

- The influence of enhanced throttle control and reduced speed oscillation for traffic in urban areas; and,
- The influence of enhanced gap acceptance in providing benefits from CAVs.

Conversely, where the SRN model shows the greatest relative improvements at higher penetration levels, the urban model does not. The significant improvements shown at low levels of penetration (25%, 50%) are also shown in Figure 50.

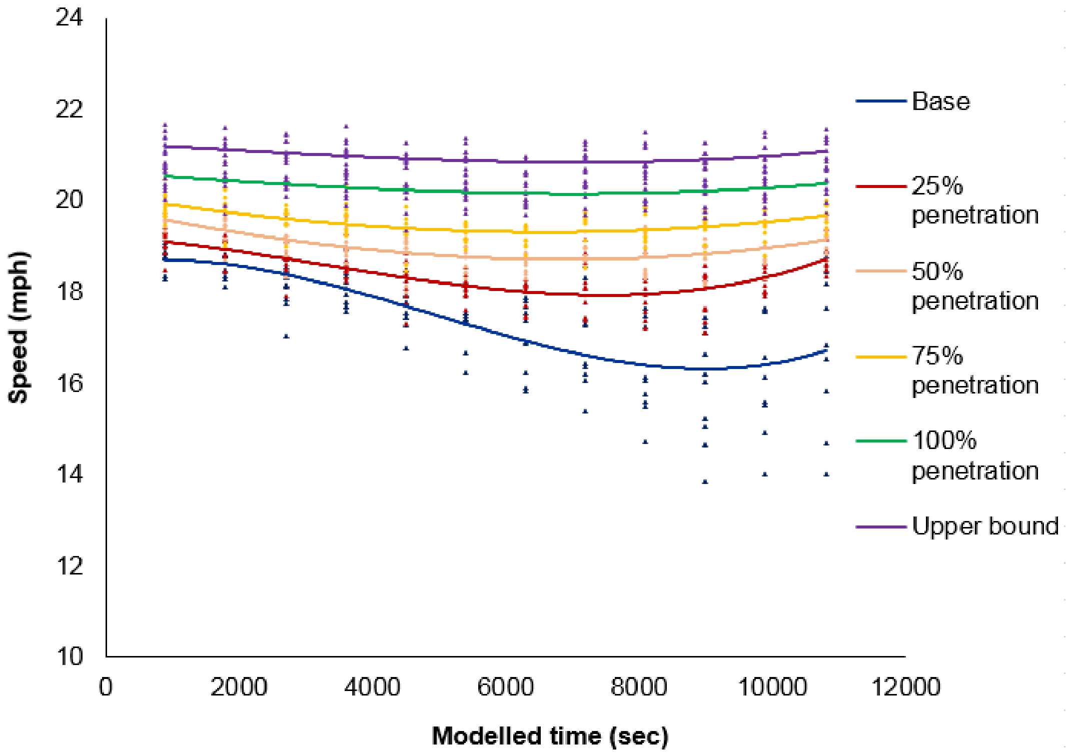
As the proportion of CAVs increases, a greater proportion of the vehicle fleet is enabled with this technology. However, as speeds are necessarily limited to a greater extent in urban areas, benefits seen on the SRN, relating to closely spaced highly automated vehicles at high speeds, are not observed. High penetration scenarios allows dense, closely spaced traffic to travel at high speed – this is less relevant for urban situations.

Figure 50: Model G network delay (peak period)



Network performance benefits are also shown in network average speed, as in Figure 51. Speeds over the modelled period are also more stable at a higher CAV penetration rate, even with increasing demand.

Figure 51: Model G network average speed (peak period)



Some delay benefits are evident in the low demand (non-peak) time period (Figure 52). This is likely due to immediate behaviour at the stop line, with individual vehicles benefiting.

Figure 52: Model G network delay by simulation time (non-peak period)

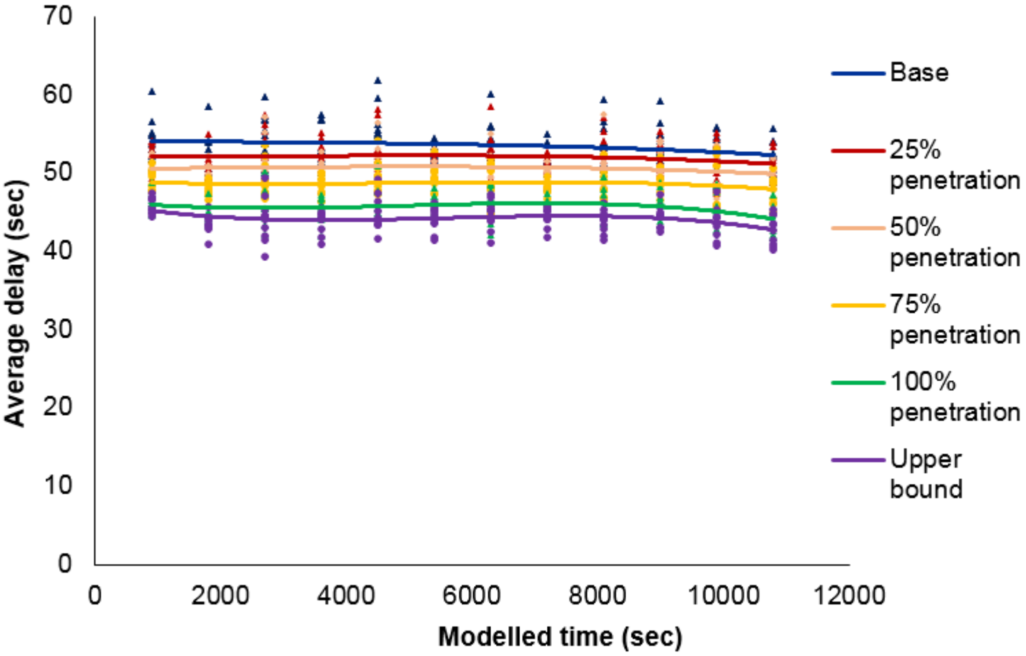
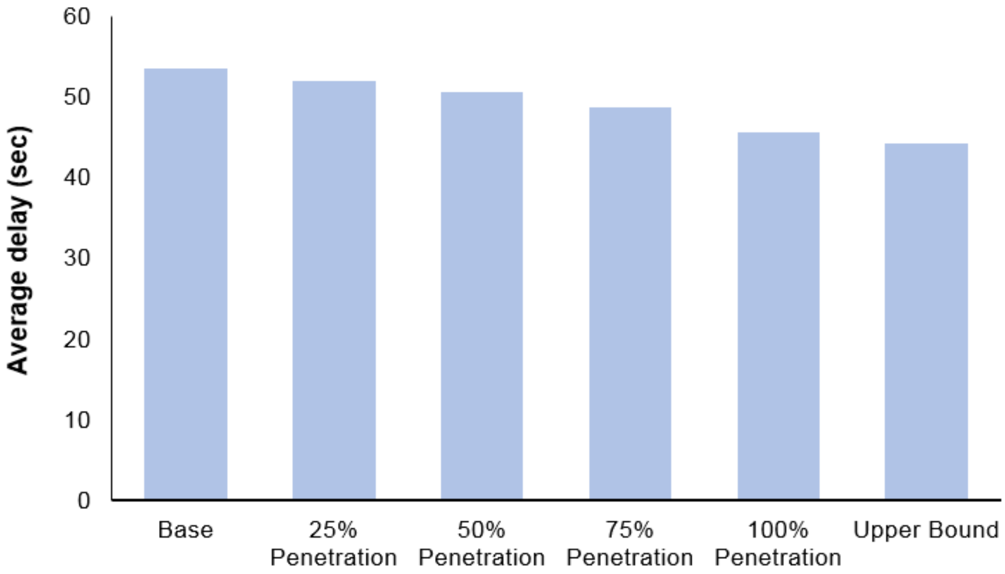


Figure 53 demonstrates the average network delay over the entire modelled time period. Again, the impacts of increasing penetration are clear and expected, but smaller in an uncongested situation.

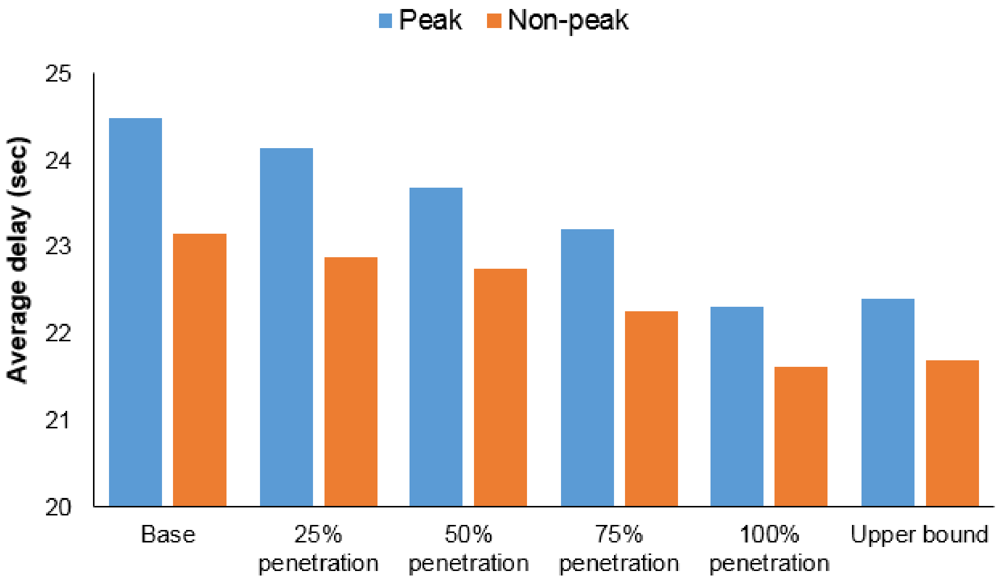
Figure 53: Model G network delay (non-peak period)



Junction performance

Figure 54 shows average delay for the signalised junction during the peak demand period. Improvement in successive scenarios appears more stable than compared to network performance metrics. Again, the benefits of introducing CAVs are more clearly shown in the peak period.

Figure 54: Model G signalised junction average delay (peak period)



In this case, the “upper bound” does not represent the best modelled case, with slightly lower benefits than 100% penetration. It is worth noting that the signalised junction uses fixed signal times, and therefore may not be optimised for the changing traffic condition caused by increasing penetration of CAVs. This may also be attributed to general variability of the model runs. Although 10 model runs have been carried out for each scenario, there may not have accounted for the randomness of the traffic.

Travel Time

In Model G, travel time for both the legacy fleet and CAV are collected for the southbound journey, identified as the most congested section of the network and the main through route. The journey time segment is shown in Figure 55.

Figure 55: Model G journey time segment

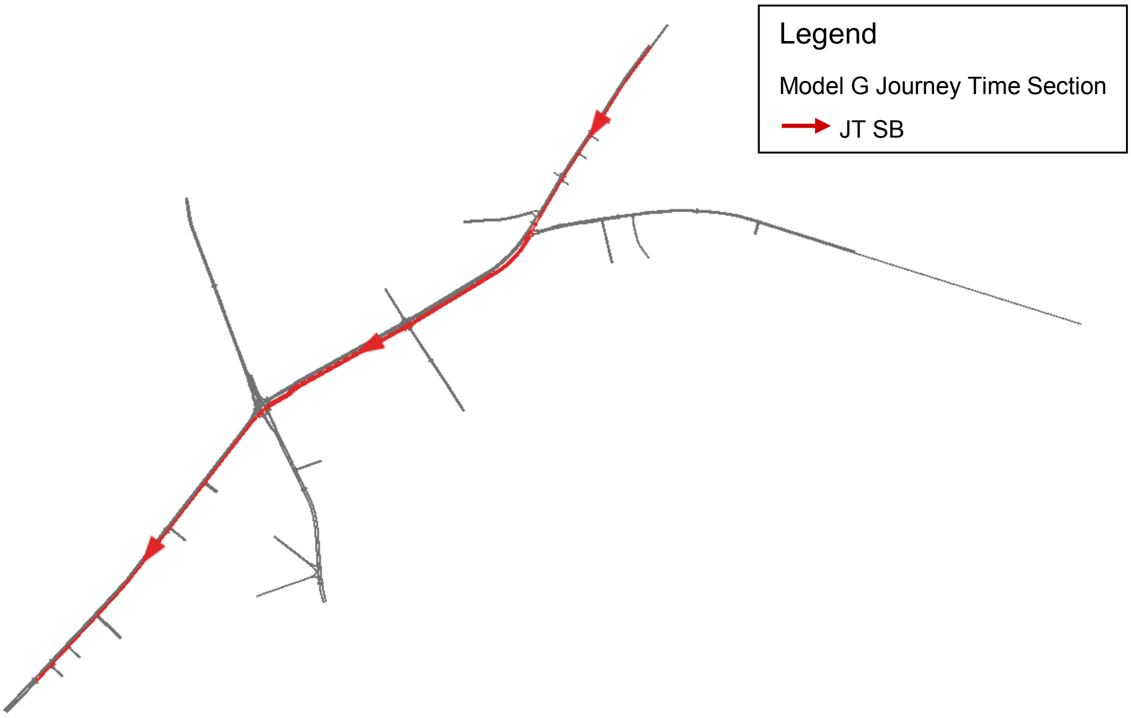


Figure 56 shows a box-and-whisker plot of journey times for the route of the urban model. The introduction of CAVs results in a much more constrained range of journey times in the model. This is akin to reliability of journey times.

Figure 56: Model G journey times (peak period)

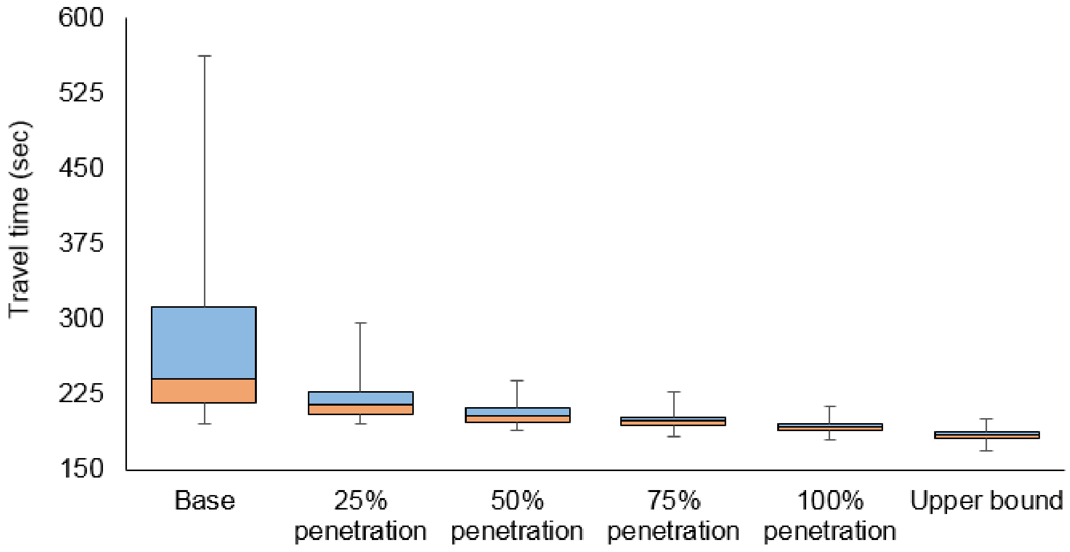
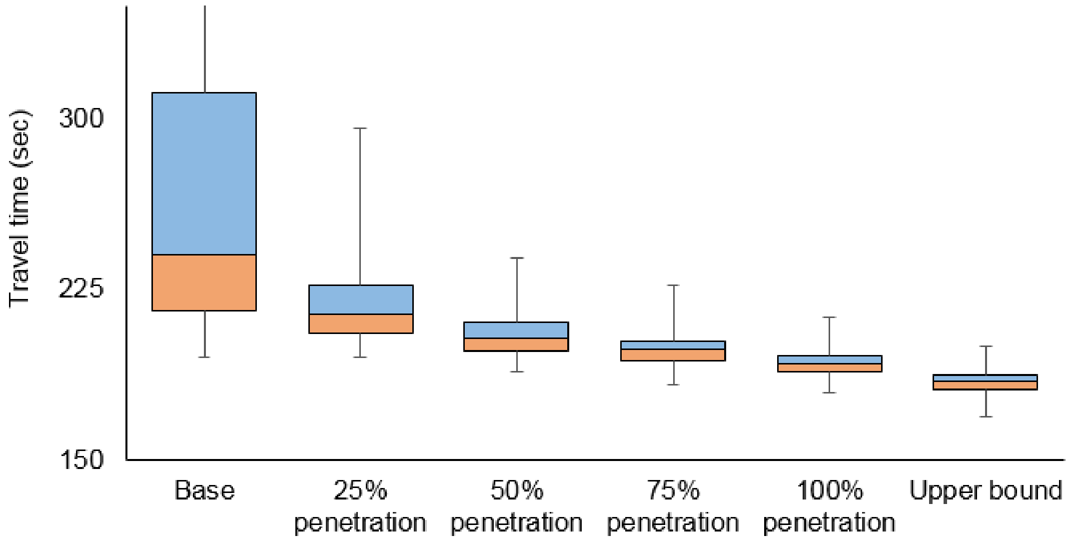


Figure 57 shows this trend in more detail for higher penetrations of CAVs. Journey times generally reduce and are subject to a smaller range, showing the increased reliability.

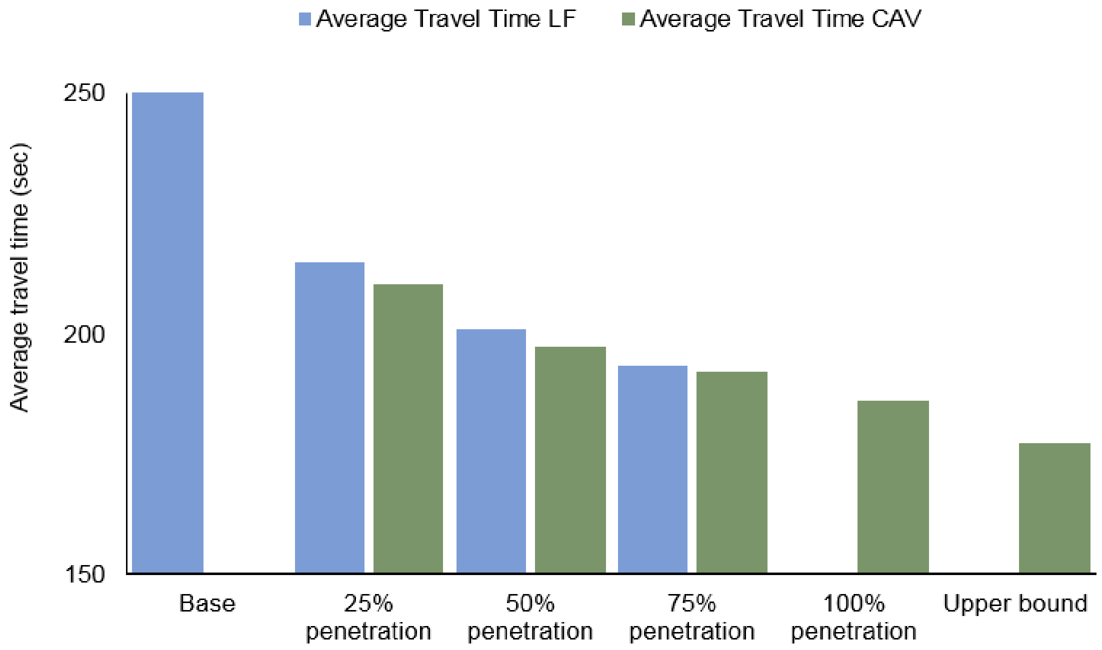
Figure 57: Model G journey times (peak period) – enhanced view



Poor journey time reliability is a characteristic of congested networks. As such, the enhanced behaviour displayed by CAVs in these models is likely to cause improvements to delay, journey time and journey time reliability as a result of increased operational road capacity and smoother traffic flow.

Journey time benefits are also calculated separately for legacy fleet and CAVs. As the journey time in peak period is more critical, results for the peak period are discussed. The average journey times over the modelled period for each penetration level are shown in Figure 58.

Figure 58: Model G journey time by vehicle type (peak period)



As with the SRN model, benefits are to all network users, but are greater for connected and autonomous vehicles. Table 20 summarises the journey time results.

Table 20: 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

5. Summary and conclusions

This chapter draws together the conclusions from the modelling and analysis, makes clear the limitations of this study, and identifies particular areas of further work.

5.1. Summary results

This section summarises the results across the complex model scenarios (SRN and urban), previously shown in Section 4.3. Simple model results are discussed in Section 3.3. The following metrics are used:

- Average delay across the whole network, in seconds;
- Average journey time for the main route, in seconds (for the SRN model, JTa is used);
- Variability in journey time, taken as the standard deviation, in seconds; and,
- The coefficient of variation (the ratio of the standard deviation to the mean).

To aid in this, Table 21 summarises the different CAV penetration scenarios used in each scenario.

Table 21: 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%*
1	75%	25%	*20%*	*1.25%*	*1.25%*	*1.25%*	*1.25%*	*0%*
2	50%	50%	*35%*	*2.5%*	*2.5%*	*2.5%*	*2.5%*	*5%*
3	25%	75%	*50%*	*3.75%*	*3.75%*	*3.75%*	*3.75%*	*10%*
4	0%	100%	*40%*	*10%*	*10%*	*10%*	*10%*	*20%*
5	0%	100%	*0%*	*0%*	*0%*	*0%*	*0%*	*100%*

5.1.1. SRN model, peak period

Table 22 shows summary results for the SRN model during the peak (congested period).

Table 22: Summary results – SRN model (segment JTa), 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%*

The major findings are shown below. Further detail is included in Section 4.2 of this report.

- The low CAV penetration case (25%) results in only minor benefits to journey time, and small disbenefits to average delay. This is attributed to the presence of a minority of cautious CAVs (more cautious than the vehicle fleet), which may impede the progress of other vehicles.
- 50% penetration of CAVs results in around 7% improvements to delay, 1% improvements to average journey time, and an 11% improvement to the variability of journey times[12].
- Journey time benefits are 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%.

5.1.2. SRN model, HGV-only case, peak period

Table 23 shows summary results for the HGV-only case for the SRN model, conducted for the peak demand situation.

Table 23: Summary results – SRN model, non-peak period

Scenario	Average delay (s)		Average journey time (s)		Journey time variability (s)		Coefficient of variation	
	(s)	%	(s)	%	(s)	%		%
Base	35.84	*0.0%*	539.79	*0.0%*	20.17	*0.0%*	0.0374	*0.0%*
(1) 25% CAV	36.79	*2.7%*	540.29	*0.1%*	19.35	*-4.0%*	0.0358	*-4.1%*
(2) 50% CAV	36.14	*0.9%*	539.12	*-0.1%*	18.96	*-6.0%*	0.0352	*-5.9%*
(3) 75% CAV	36.10	*0.7%*	536.91	*-0.5%*	17.56	*-13.0%*	0.0327	*-12.5%*
(4) 100% CAV	36.14	*0.8%*	535.61	*-0.8%*	17.16	*-14.9%*	0.0320	*-14.3%*
(5) Upper bound	32.73	*-8.7%*	527.25	*-2.3%*	15.93	*-21.0%*	0.0302	*-19.1%*

Benefits are much smaller as HGVs only make up a small proportion of the total vehicle fleet (around 14% in this model). However, improvements around variability and reliability are still strong, particularly in higher penetration scenarios. This demonstrates the potential improvements a minority of vehicles can make.

5.1.3. SRN model, non-peak period

Table 24 shows summary results for the SRN model in the “non-peak”, uncongested period. Again, journey time is shown for segment JTa.

- There are improvements to average delay and average journey time with successive scenarios. Benefits are much smaller, in line with the expectations in an uncongested situation.
- Benefits to variability and reliability in journey times are not clear, and are likely to be more closely related to the variability of traffic in the simulation than any particular mechanism associated with connected and autonomous vehicles.

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[12] Taken as the coefficient of variation

Table 24: Summary results – 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%*

5.1.4. Urban model, peak period

Table 25 shows summary results for the urban model during the peak (congested period). Journey times are shown for the main through route, as discussed in Section 4.3.2.

Table 25: 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%*

- Large improvements are evident with only a small (25%) penetration of CAVs. This is attributed to the immediate benefits of improved throttle control and maintenance of speed.
- The relative benefits of higher CAV penetration are not as apparent as in the SRN model scenarios. As traffic does not exceed 30mph in the urban model, the benefits for high-flow, high-speed traffic are less acutely felt.

5.1.5. Urban model, non-peak period

Table 26 shows summary results for the urban model in the “non-peak”, uncongested period.

Table 26: Summary results – 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%*

- There are incremental improvements to delay and journey time with successive implementations of CAVs. The major improvements are around variability, with an improvement of around 50%.
- A low penetration of CAVs (25%) producing only a small improvement in delay and journey time (less than 3%) can still demonstrate a reduction in journey time variability or nearly 30%. This is a key result.

5.2. Conclusions

The mechanisms by which connected and autonomous vehicles could impact traffic flow 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 disruptions to traffic flow and capacity, 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 worsening of measures of network performance and road capacity**, especially in high-speed, high-flow situations (such as the SRN). In the complex models (Section 4), this can be illustrated by changing measures of network performance, such as network delay and journey times. For more straightforward situations (such as the simple models discussed in Section 3), this can be described through changes in capacity.

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

There is great potential for significant capacity, delay and journey time benefits, 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 – average journey time, delay and capacity – have been shown to generally improve with increasing penetration and capability of CAVs. However, there is also evidence that reliability will also improve[13]. 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.

5.3. Limitations and 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;

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

- 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.

5.3.1. 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.

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 the series of simple models, discussed in Chapter 3.

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.

5.3.2. 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[14], 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.

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.

5.3.3. 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).

5.3.4. 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.

5.3.5. 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.

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[14] From, for example, Highways England data sources

Appendices

Appendix A. VISSIM parameters

A.1. Car-following model parameters (Wiedemann 99)

The following has been adapted from PTV VISSIM documentation:

- ***Look ahead distance:*** defines the distance that a vehicle can see forward in order to react to other vehicles either in front or to the side of it (within the same link). This parameter is in addition to the number of Observed Vehicles.
- ***Observed vehicles***: affects how well vehicles in the network can predict other vehicles' movements and react accordingly.
- ***Look back distance***: defines the distance that a vehicle can see backwards in order to react to other vehicle behind.
- ***Smooth closeup behavior***: If this option is checked, vehicles slow down more evenly when approaching a standing obstacle.
- ***Desired Speed Distribution***: The speed that each vehicle is trying to achieve if it is lower than the max speed limit on the link.
- ***CC0 (Standstill distance)***: defines the desired distance between stopped cars. It has no variation***.***
- ***CC1 (Headway time)***: is the time (in seconds) that a driver wants to keep. The higher the value, the more cautious the driver is. Thus, at a given speed v [m/s], the safety distance dx_safe is computed to: dx_safe = CC0 + CC1 • v.
- ***CC2 ('Following' variation)***: restricts the longitudinal oscillation or how much more distance than the desired safety distance a driver allows before he intentionally moves closer to the car in front. If this value is set to e.g. 10m, the following process results in distances between dx_safe and dx_safe + 10m. The default value is 4.0m which results in a quite stable following process.
- ***CC3 (Threshold for entering 'Following')***: controls the start of the deceleration process, i.e. when a driver recognizes a preceding slower vehicle. In other words, it defines how many seconds before reaching the safety distance the driver starts to decelerate.
- ***CC4 and CC5 ('Following' thresholds***) control the speed differences during the 'Following' state. Smaller values result in a more sensitive reaction of drivers to accelerations or decelerations of the preceding car, i.e. the vehicles are more tightly coupled. CC4 is used for negative and
- ***CC5 for positive speed differences***: The default values result in a fairly tight restriction of the following process.
- ***CC6 (Speed dependency of oscillation***): Influence of distance on speed oscillation while in following process. If set to 0 the speed oscillation is independent of the distance to the preceding vehicle. Larger values lead to a greater speed oscillation with increasing distance.
- ***CC7 (Oscillation acceleration***): Actual acceleration during the oscillation process.
- ***CC8 (Standstill acceleration***): Desired acceleration when starting from standstill (limited by maximum acceleration defined within the acceleration curves)
- ***CC9 (Acceleration at 80 km/h***): Desired acceleration at 80 km/h (limited by maximum acceleration defined within the acceleration curves).

Appendix B. Simple model parameter variations

B.1. Model A (single-lane) link

Capability level	CC0 (m)	CC1 (s)	CC7 (m/s^2)	dx_{safe} (m)
9	0.5	0.5	0.45	13.91
8	0.5	0.6	0.40	16.59
7	1.0	0.7	0.35	19.78
6	1.0	0.8	0.30	22.46
5	1.5	0.9	0.25	25.64
4	2.0	1.2	0.20	34.19
3	2.0	1.5	0.15	42.23
2	2.5	1.8	0.10	50.78
1	2.5	2.1	0.05	58.83

B.2. Model B (multi-lane link)

Capability level	CC0 (m)	CC1 (s)	CC7 (m/s^2)	LC4 (m)	LC5	dx_{safe} (m)	LC dx_{safe} (m)
9	0.5	0.5	0.45	0.2	30%	16.15	4.84
8	0.5	0.6	0.40	0.2	30%	19.28	5.78
7	1.0	0.7	0.35	0.3	40%	22.90	9.16
6	1.0	0.8	0.30	0.4	50%	26.03	13.02
5	1.5	0.9	0.25	0.5	60%	29.66	17.80
4	2.0	1.2	0.20	0.6	70%	39.55	27.69
3	2.0	1.5	0.15	0.7	80%	48.94	39.15
2	2.5	1.8	0.10	0.8	90%	58.83	52.94
1	2.5	2.1	0.05	0.8	90%	68.21	61.39

B.3. Model C (signalised junction)

Capability level	CC0 (m)	CC1 (s)	CC7 (m/s^2)	CC8 (m/s^2)	dx_{safe} (m)
9	0.5	0.5	0.45	3.9	7.21
8	0.5	0.6	0.40	3.8	8.55
7	1.0	0.7	0.35	3.7	10.39
6	1.0	0.8	0.30	3.6	11.73
5	1.5	0.9	0.25	3.5	13.57
4	2	1.2	0.20	3.4	18.09
3	2	1.5	0.15	3.3	22.12
2	2.5	1.8	0.10	3.2	26.64
1	2.5	2.1	0.05	3.1	30.66

B.4. Model D (roundabout)

Capability level	CC0 (m)	CC1 (s)	CC7 (m/s^2)	CC8 (m/s^2)	MG1 (s)	MG2 (m)	dx_{safe} (m)
9	0.5	0.5	0.45	3.9	2.2	3.0	9.44
8	0.5	0.6	0.40	3.8	2.4	3.5	11.23
7	1.0	0.7	0.35	3.7	2.6	4.0	13.52
6	1.0	0.8	0.30	3.6	2.8	4.5	15.31
5	1.5	0.9	0.25	3.5	3	5.0	17.59
4	2	1.2	0.20	3.4	3.2	5.5	23.46
3	2	1.5	0.15	3.3	3.4	6.0	28.82
2	2.5	1.8	0.10	3.2	3.6	6.5	34.69
1	2.5	2.1	0.05	3.1	3.8	7.0	40.05

B.5. Model E (multi-lane link with merge)

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)
9	0.5	0.5	0.45	3.9	1.9	0.2	30%	2.2	3.0
8	0.5	0.6	0.40	3.8	1.8	0.2	30%	2.4	3.5
7	1.0	0.7	0.35	3.7	1.7	0.3	40%	2.6	4.0
6	1.0	0.8	0.30	3.6	1.6	0.4	50%	2.8	4.5
5	1.5	0.9	0.25	3.5	1.5	0.5	60%	3.0	5.0
4	2.0	1.2	0.20	3.4	1.4	0.6	70%	3.2	5.5
3	2.0	1.5	0.15	3.3	1.3	0.7	80%	3.4	6.0
2	2.5	1.8	0.10	3.2	1.2	0.8	90%	3.6	6.5
1	2.5	2.1	0.05	3.1	1.1	0.8	90%	3.8	7.0

Appendix C. Complex 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%	3.0	5.0
Level III	*Cautious*	2.5	1.8	0.10	3.2	1.2	0.8	90%	3.6	6.5
	Normal Cautious	2.0	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

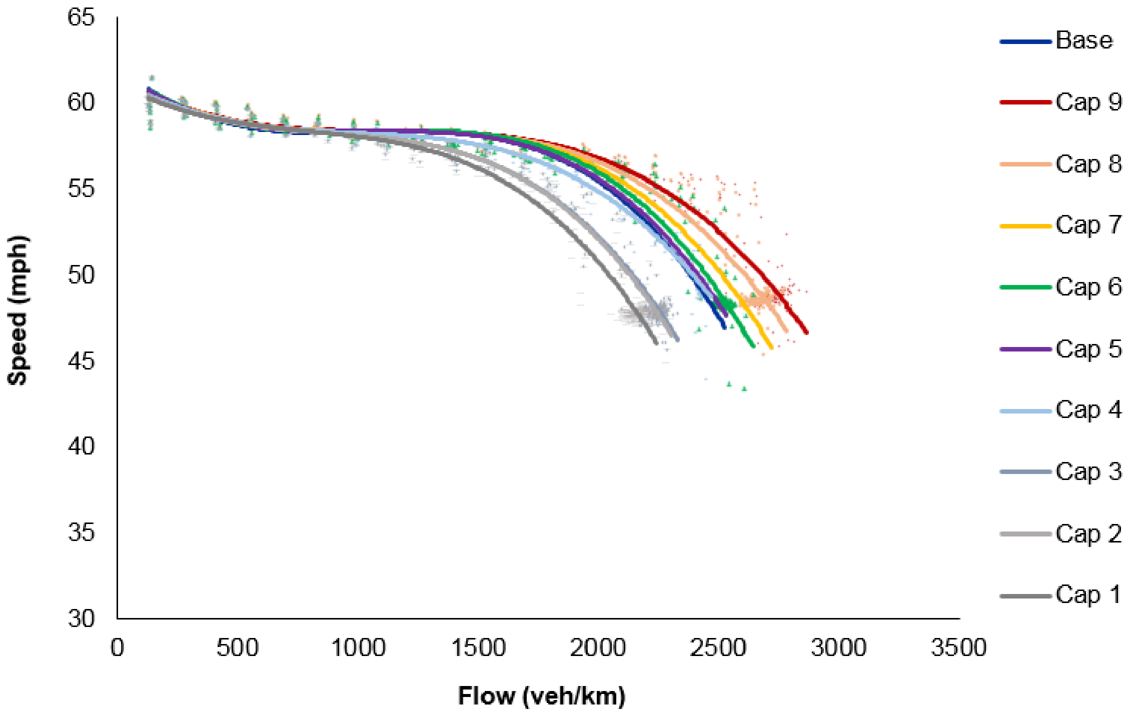
*Level IV CAVs are subject to a fixed desired speed distribution based on the defined speed limit of the link. Other CAVs and the legacy fleet are subject to the (standard) desired speed distribution according to link type in VISSIM

Appendix D. Simple model result graphs

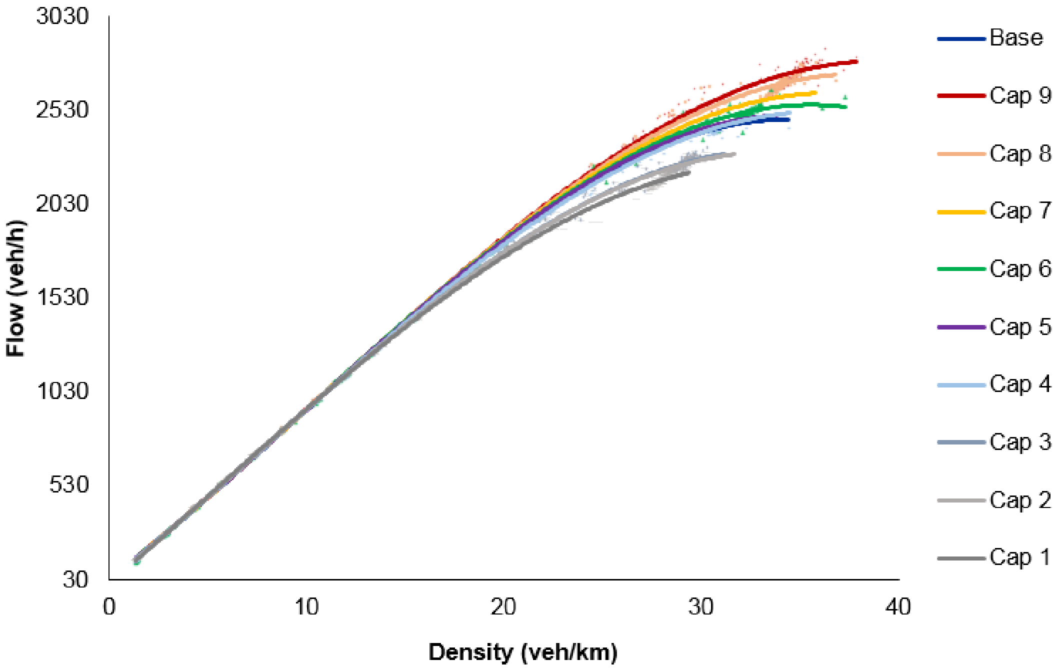
D.1. Model A (single-lane link)

D.1.1. 25% Penetration

Speed-Flow relationship

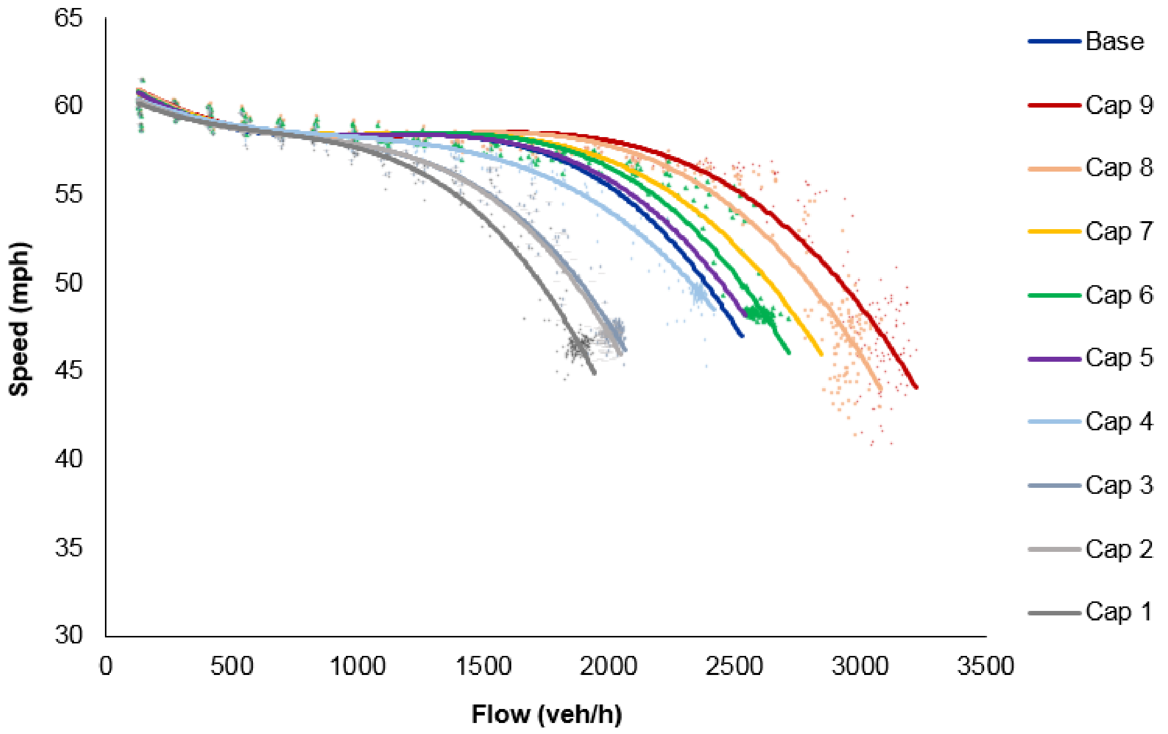


Flow-Density relationship

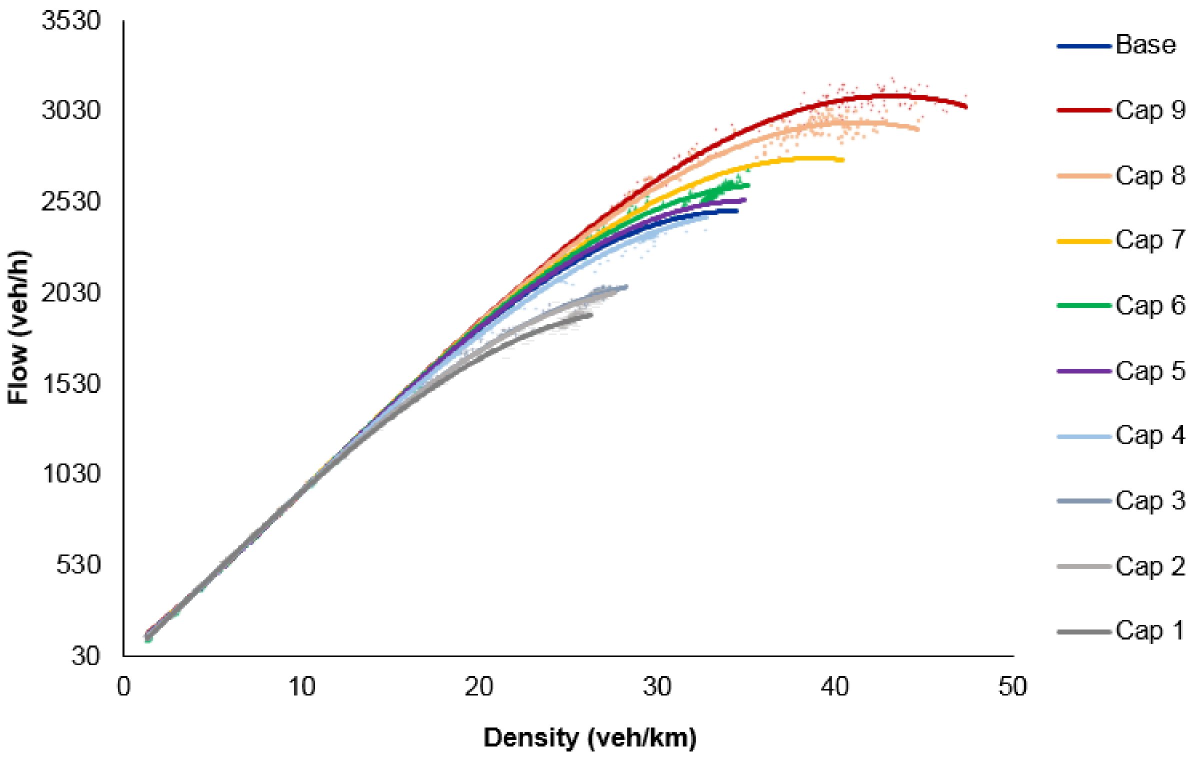


D.1.2. 50% Penetration

Speed-Flow relationship

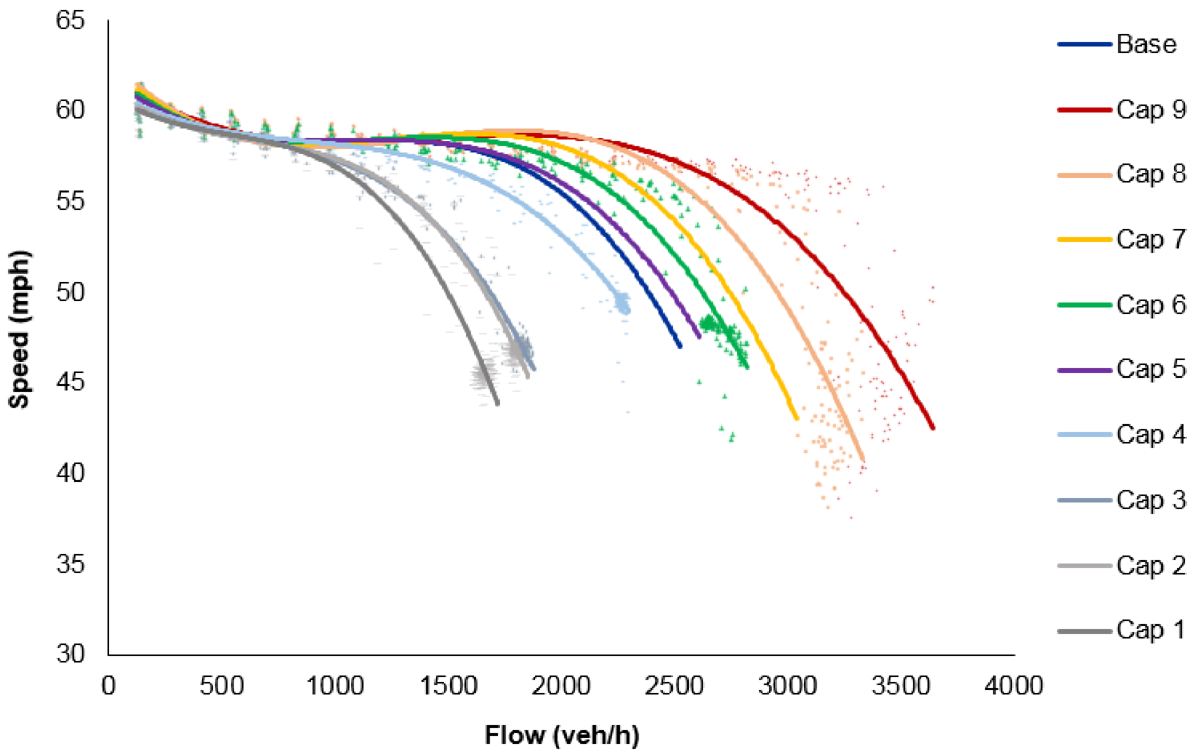


Flow-Density relationship

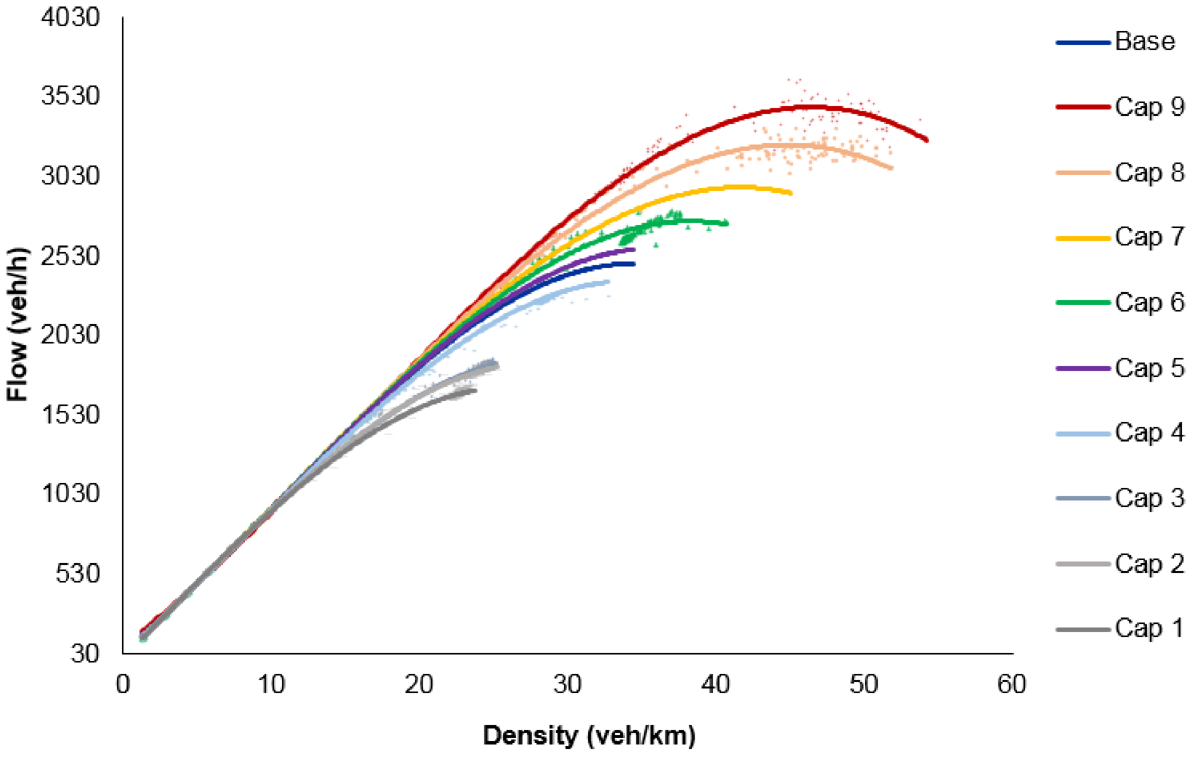


D.1.3. 75% Penetration

Speed-Flow relationship

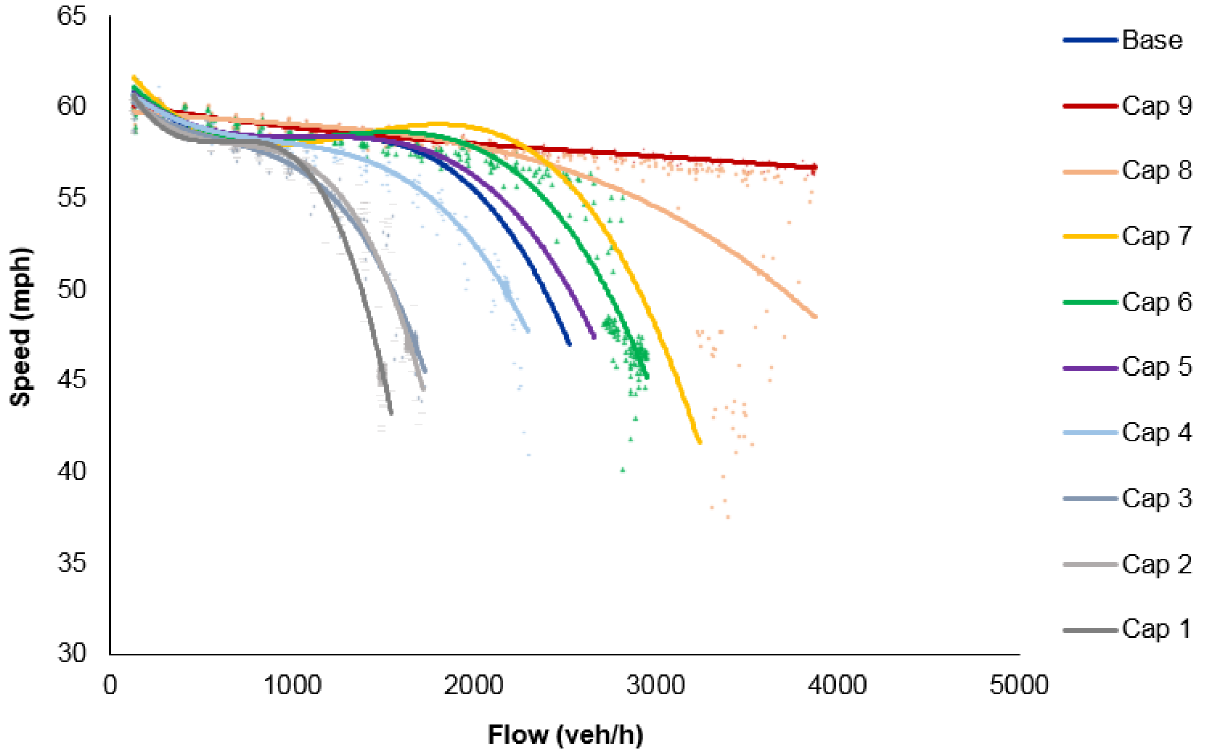


Flow-Density relationship

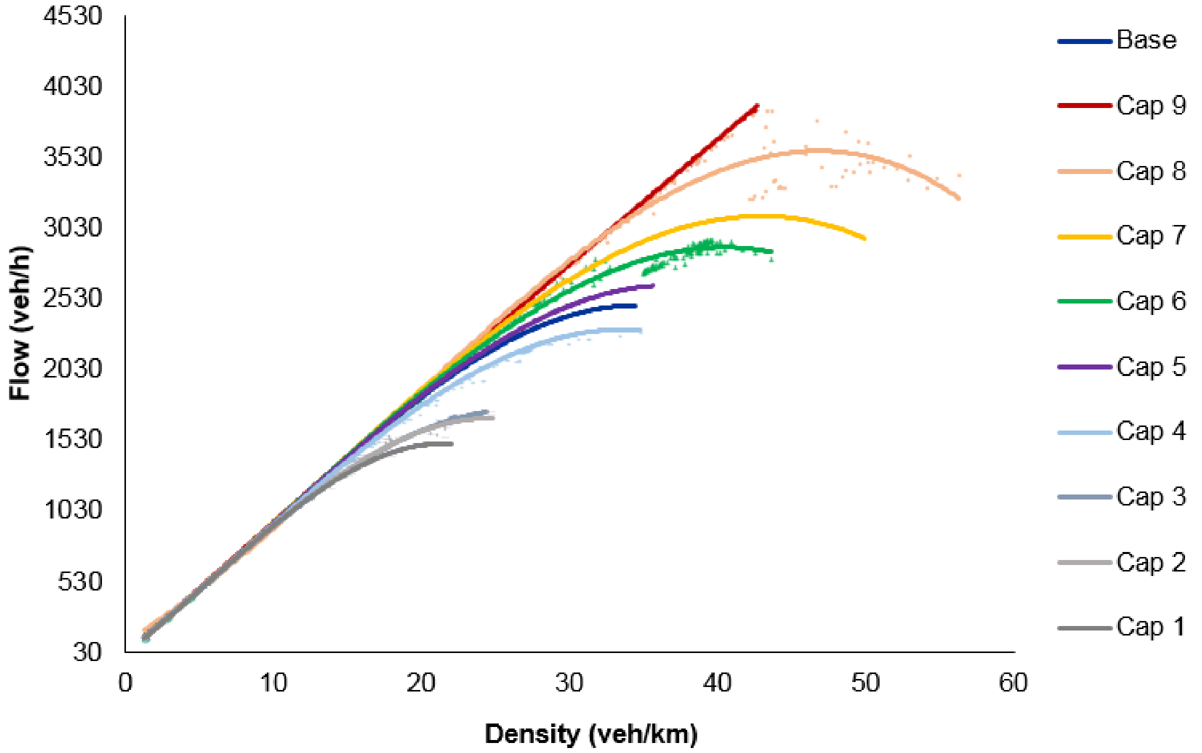


D.1.4. 100% Penetration

Speed-Flow relationship



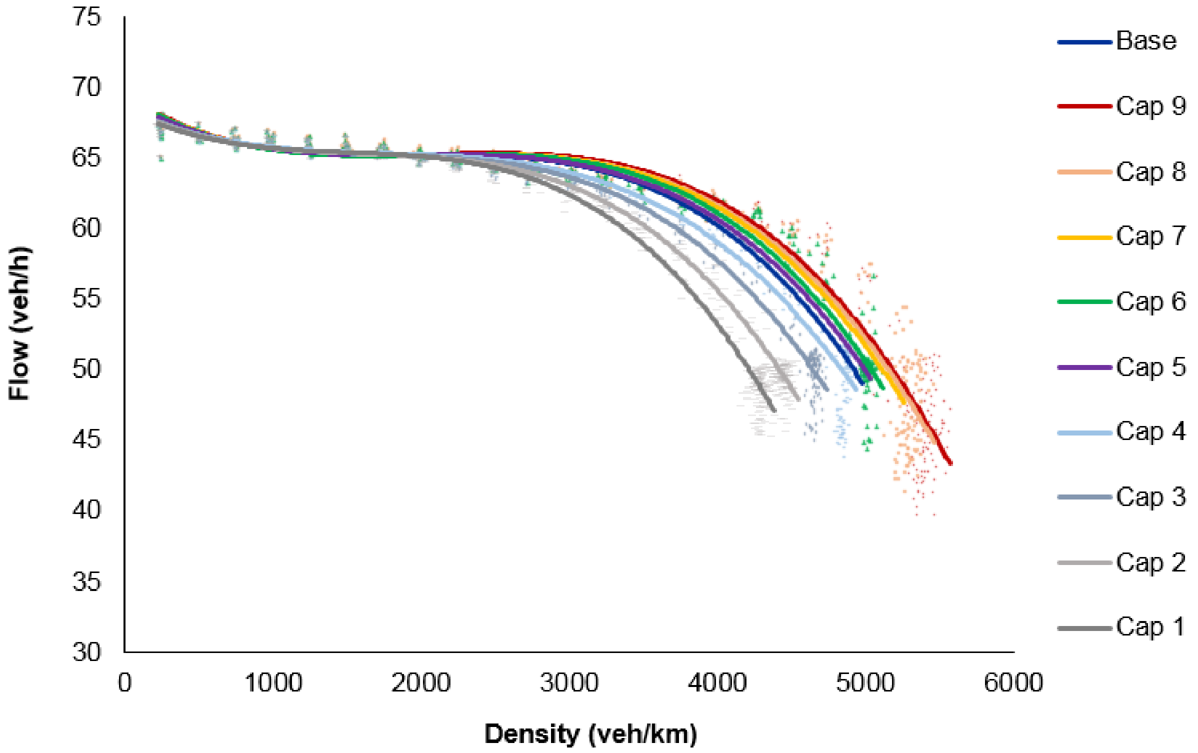
Flow-Density relationship



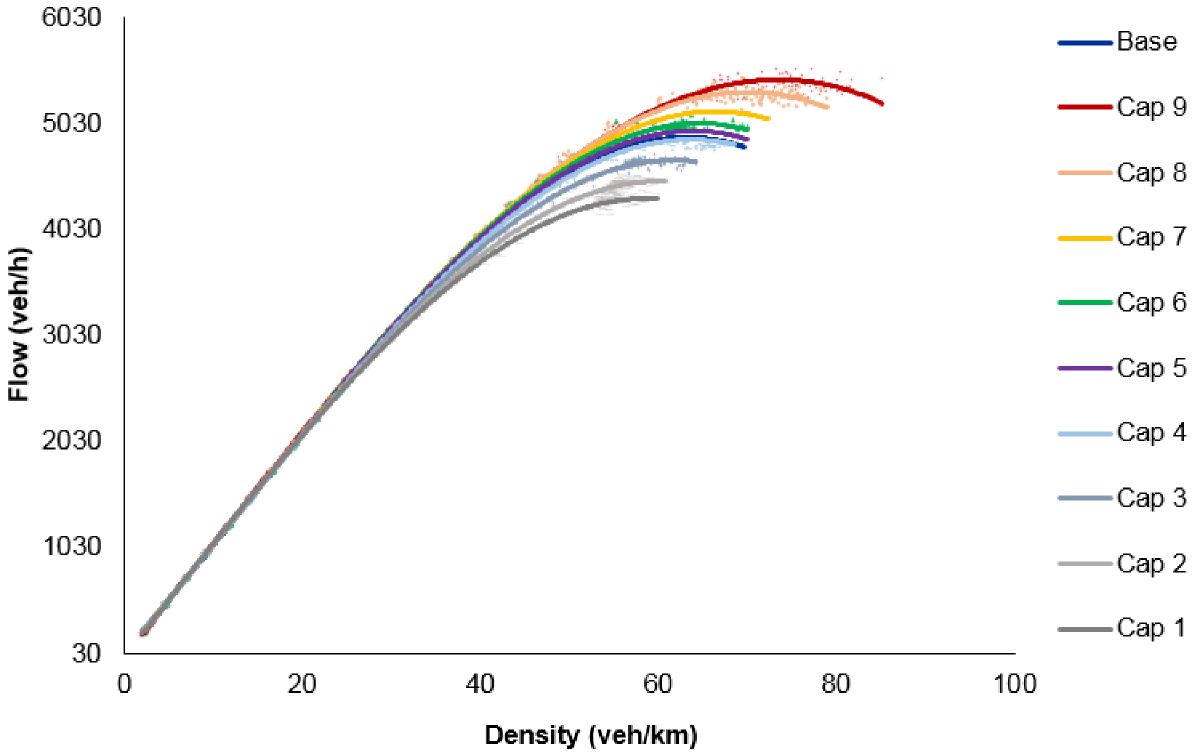
D.2. Model B (multi-lane link)

D.2.1. 25% Penetration

Speed-Flow relationship

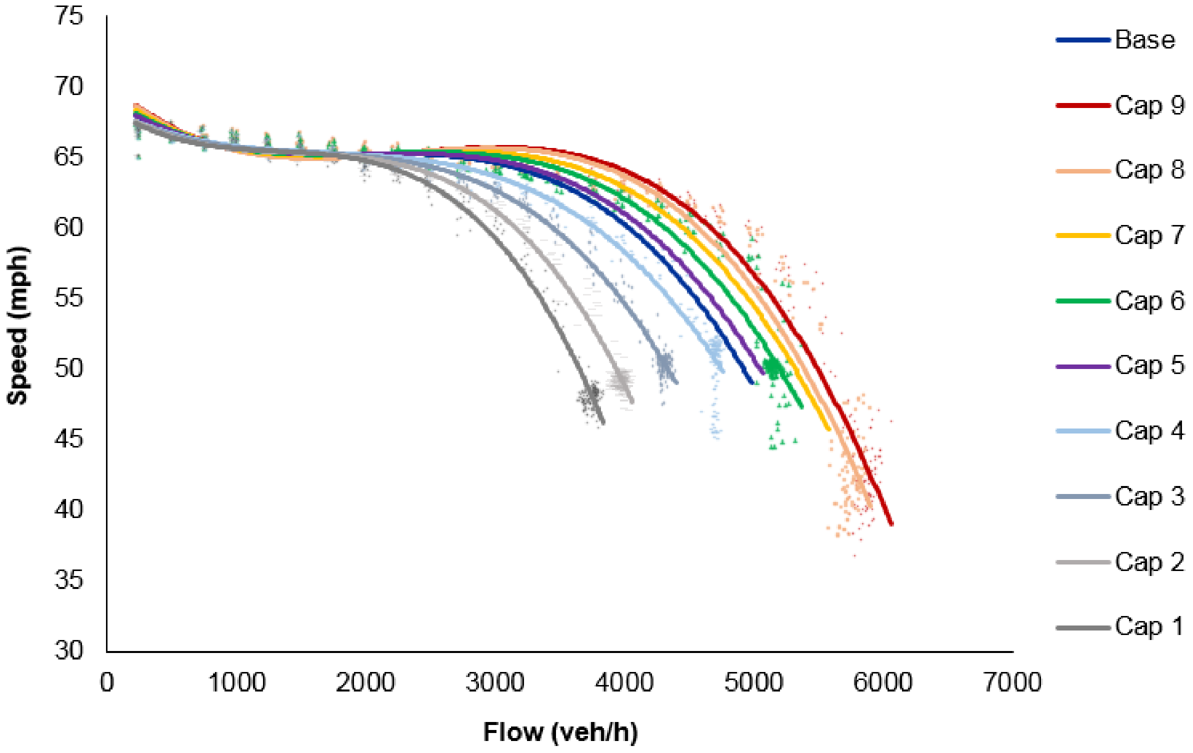


Flow-Density relationship

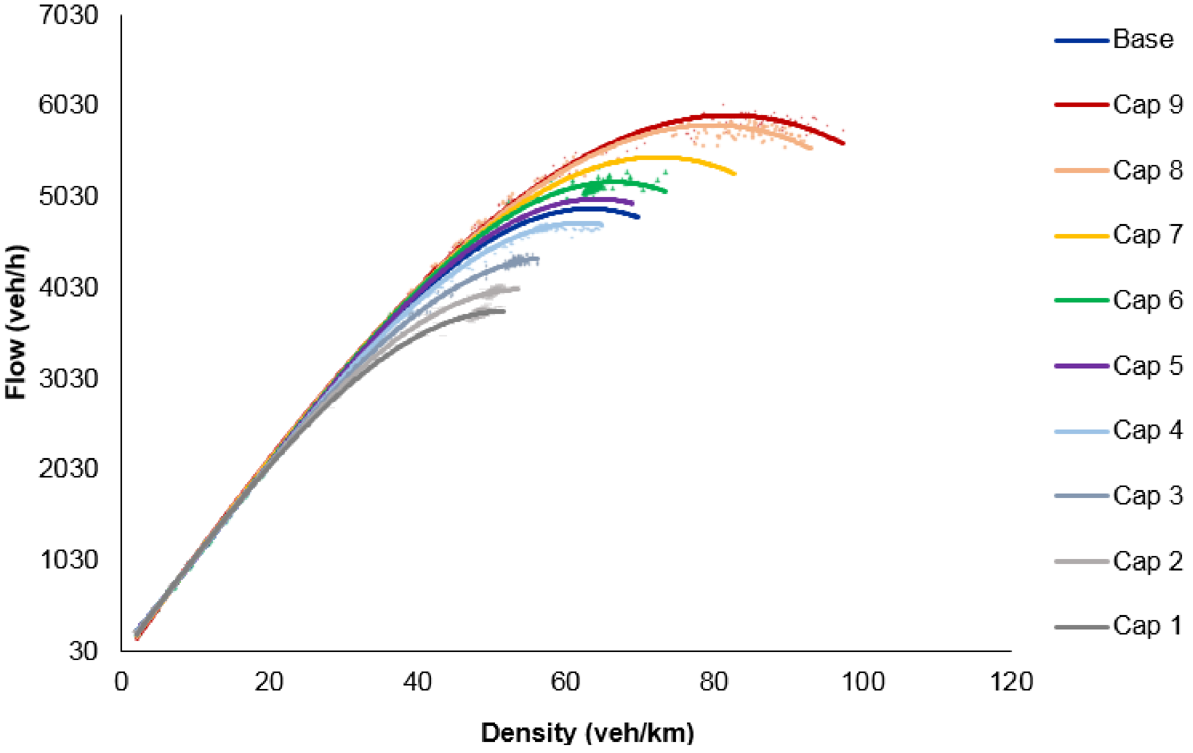


D.2.2. 50% Penetration

Speed-Flow relationship

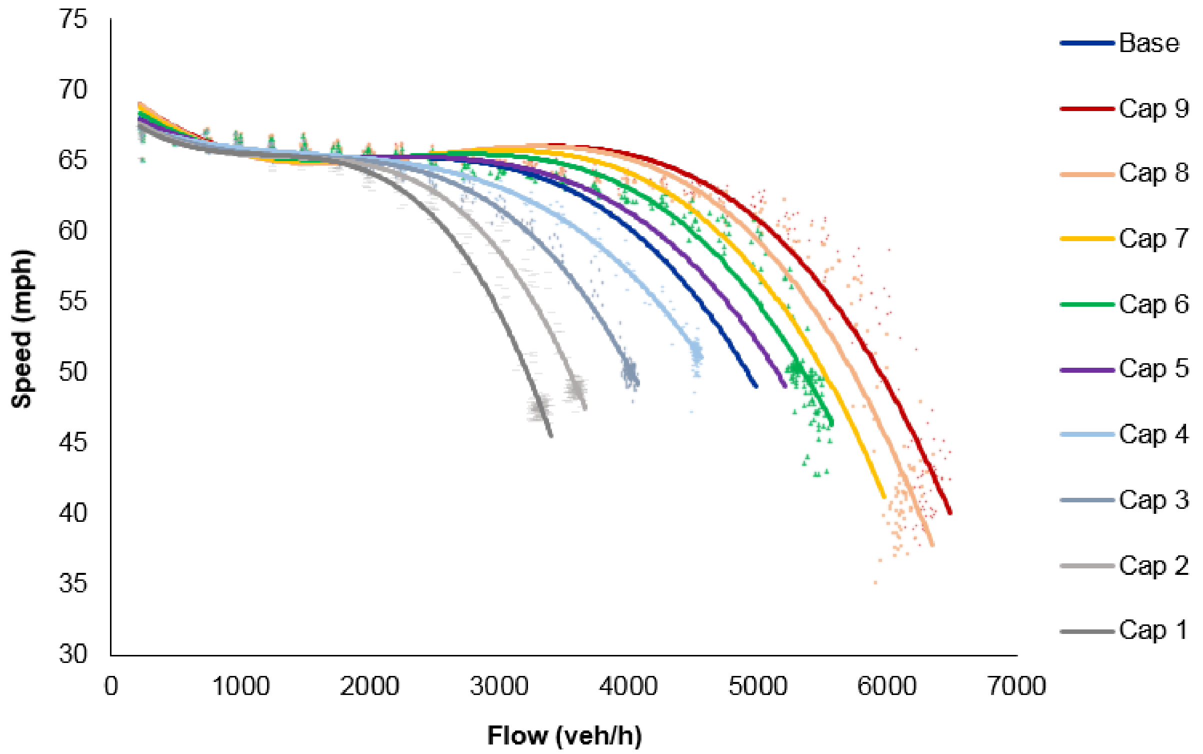


Flow-Density relationship

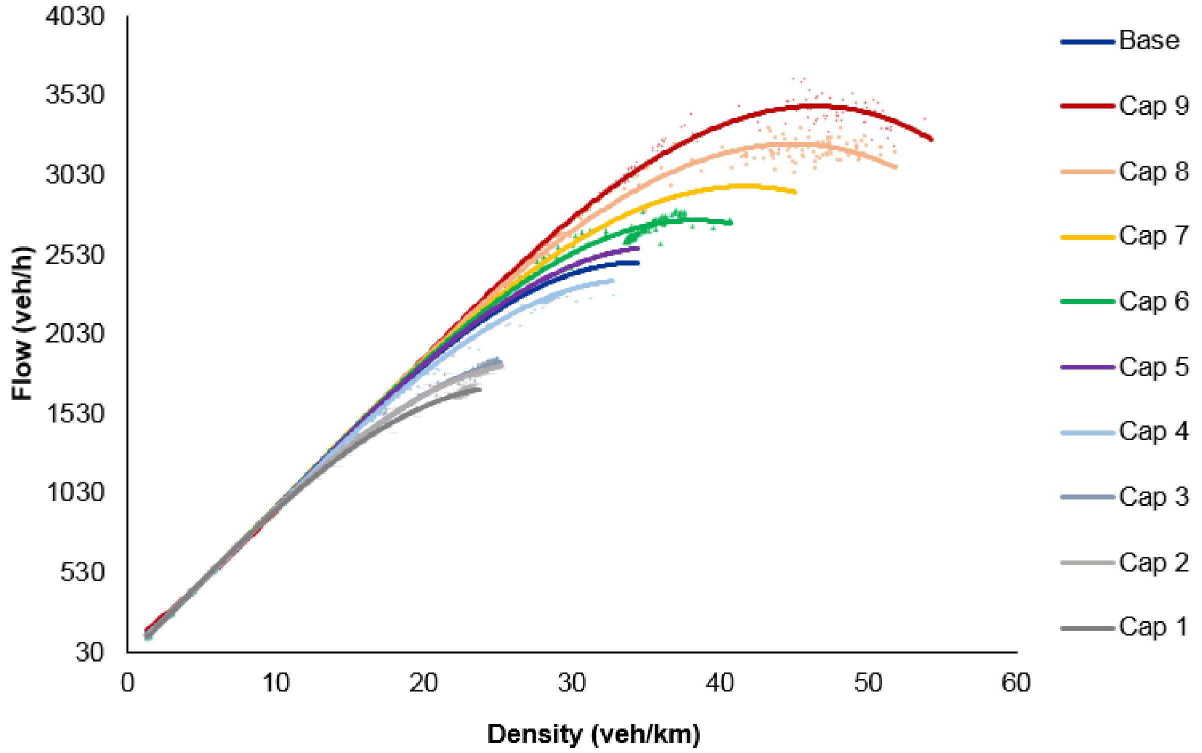


D.2.3. 75% Penetration

Speed-Flow relationship

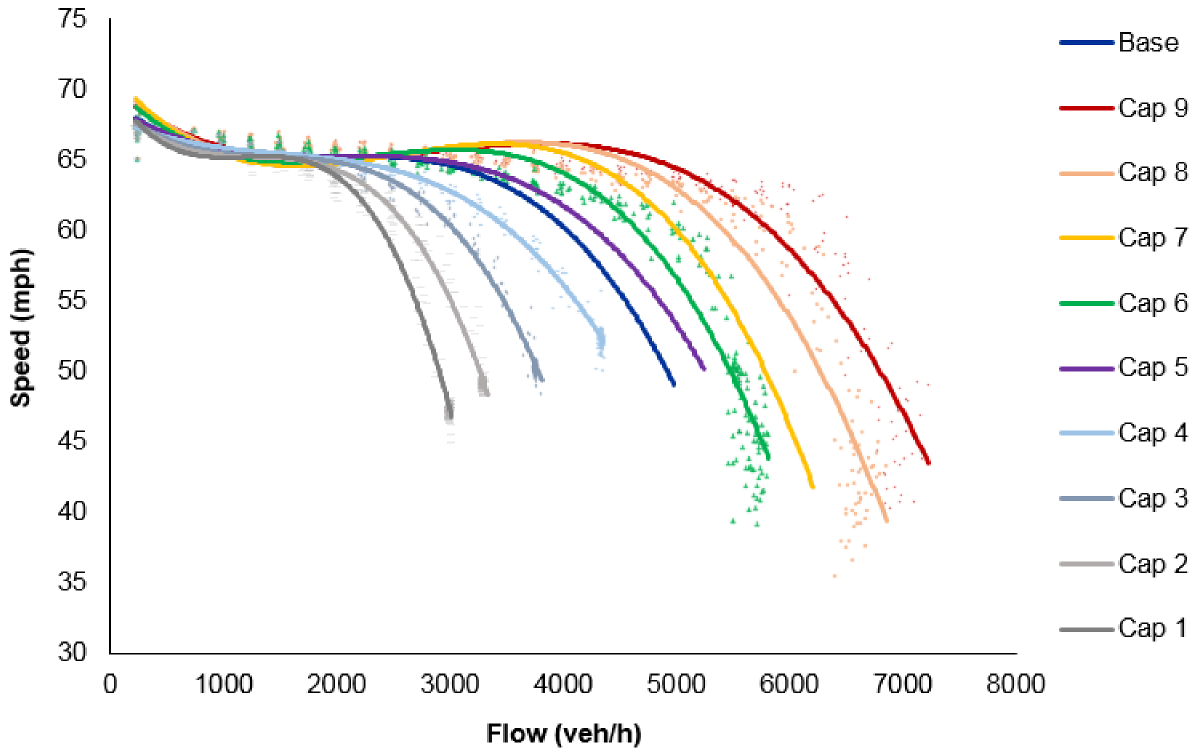


Flow-Density relationship

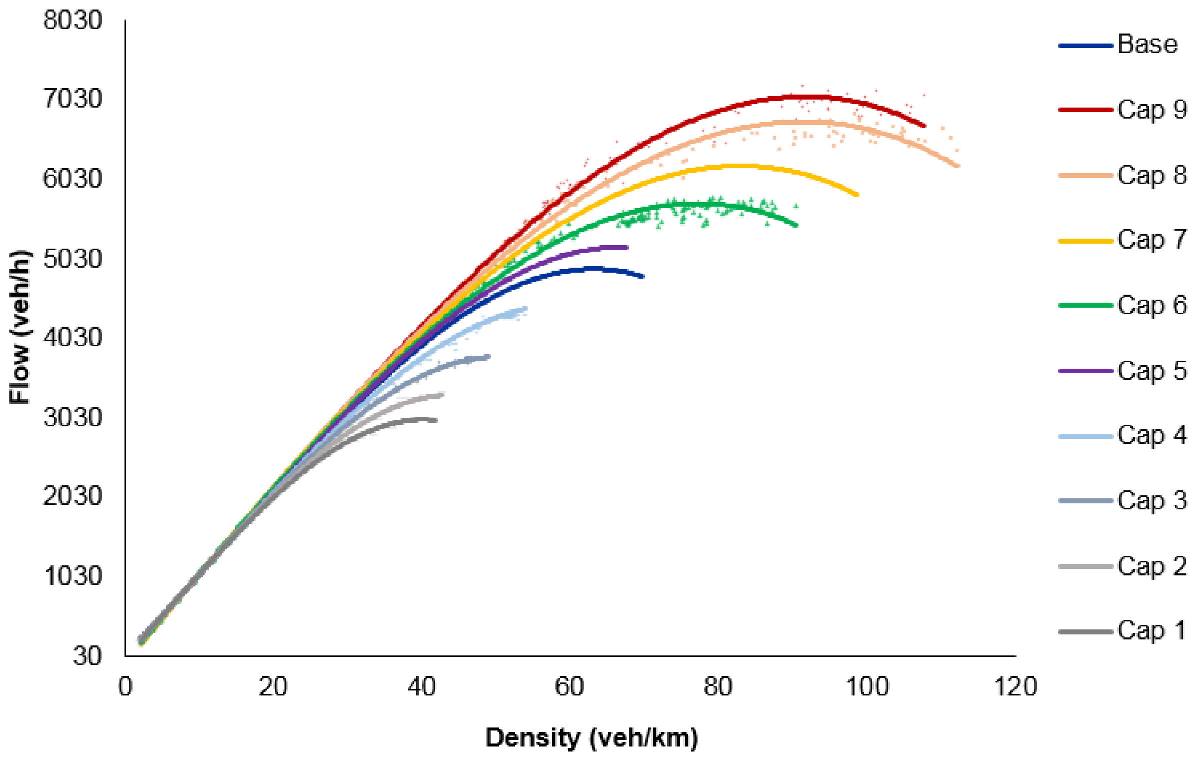


D.2.4. 100% Penetration

Speed-Flow relationship



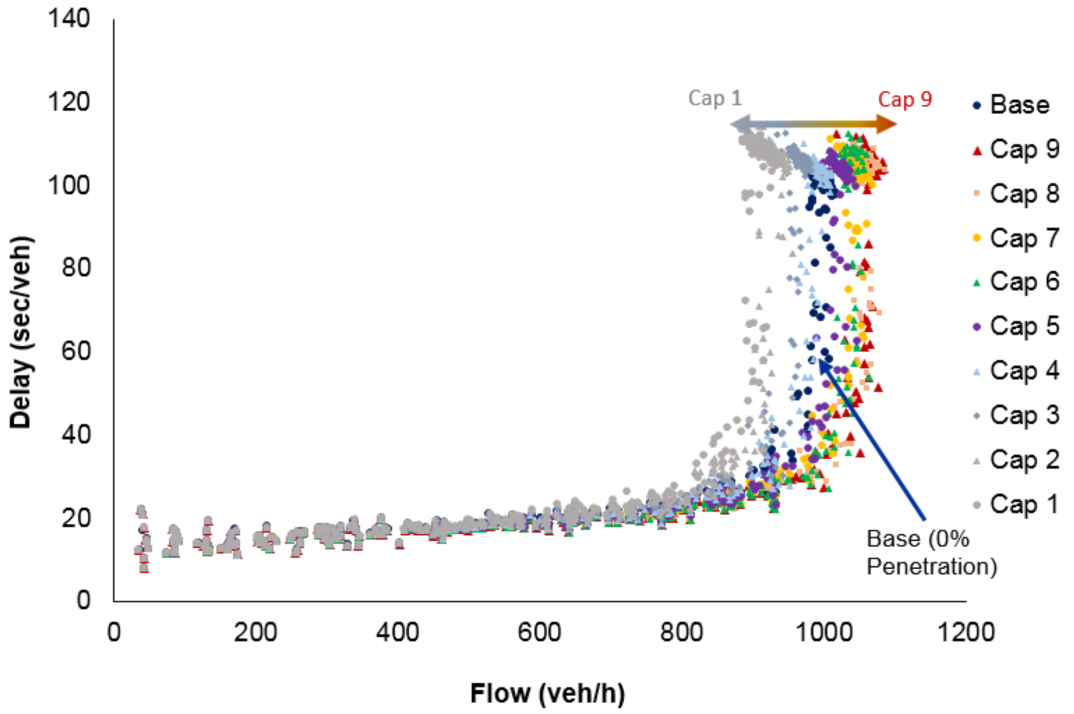
Flow-Density relationship



D.3. Model C (signalised junction)

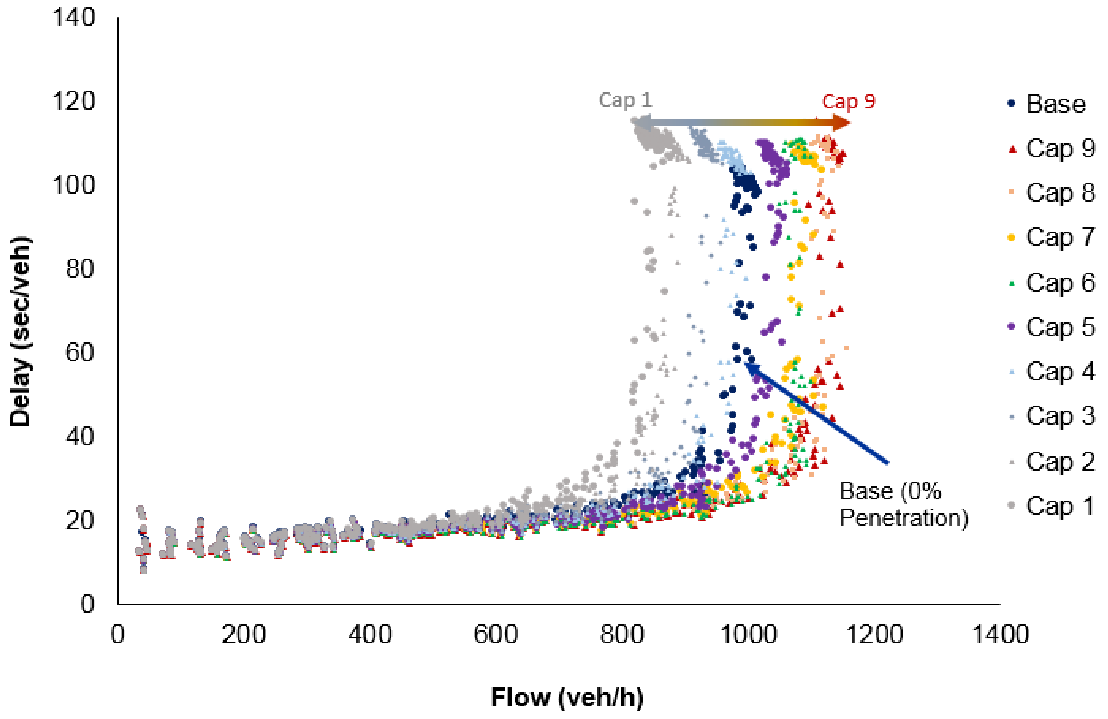
D.3.1. 25% Penetration

Average network delay



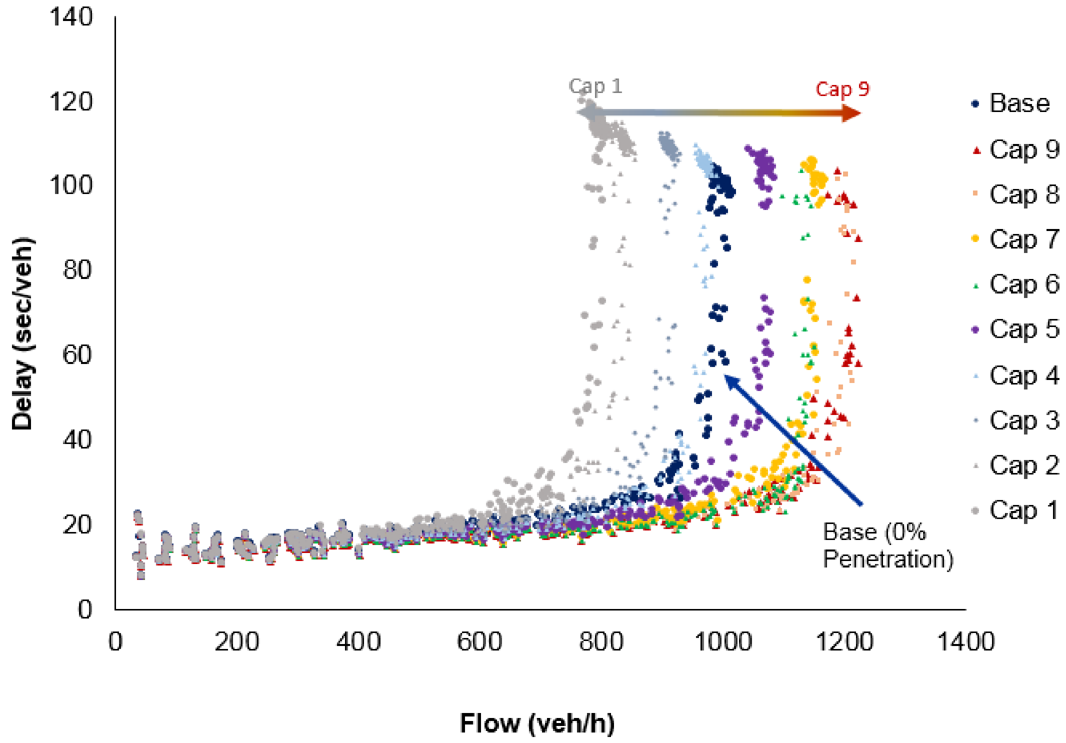
D.3.2. 50% Penetration

Average network delay



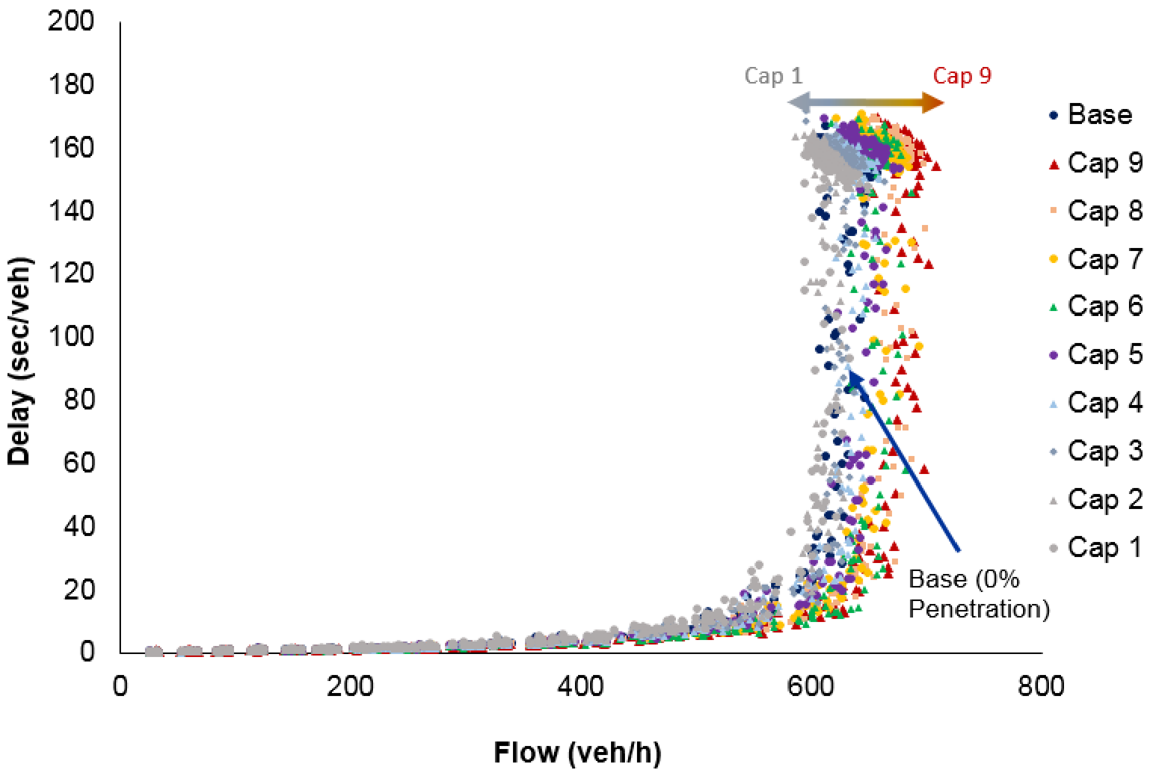
D.3.3. 75% Penetration

Average network delay



D.3.4. 100% Penetration

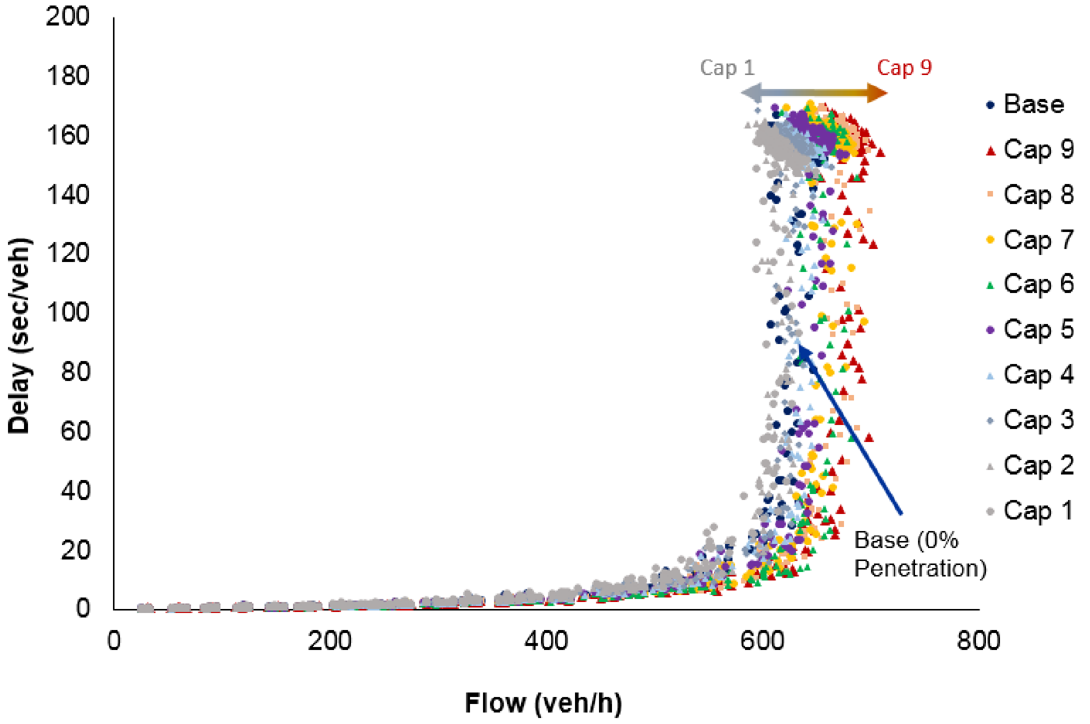
Average network delay



D.4. Model D (roundabout)

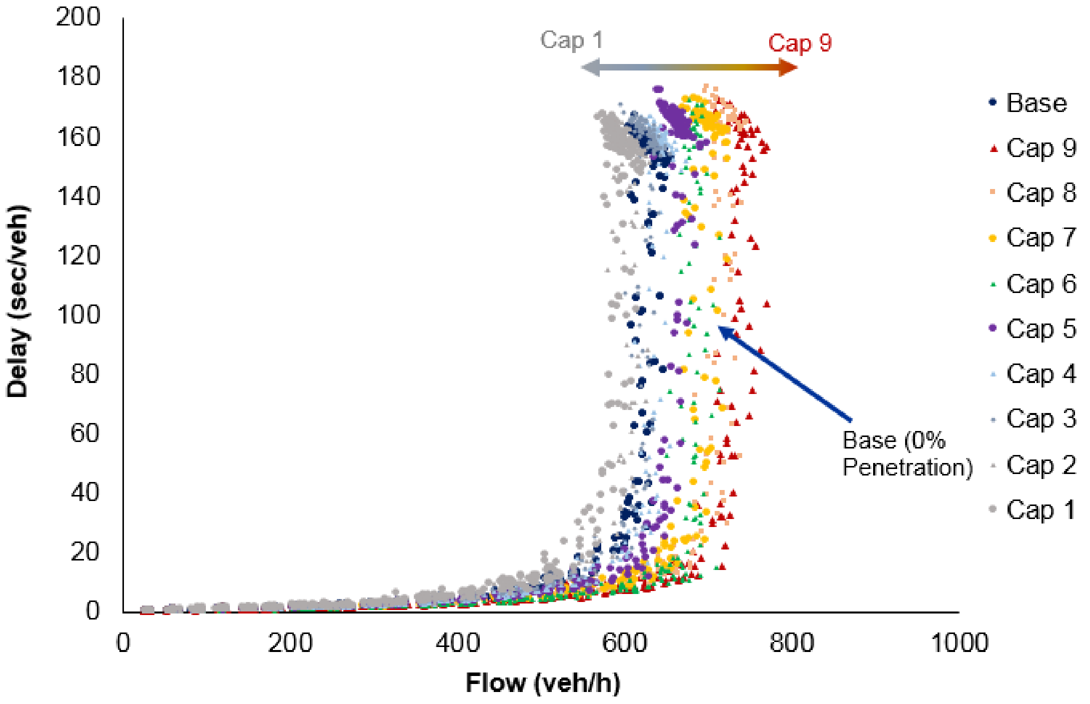
D.4.1. 25% Penetration

Average network delay



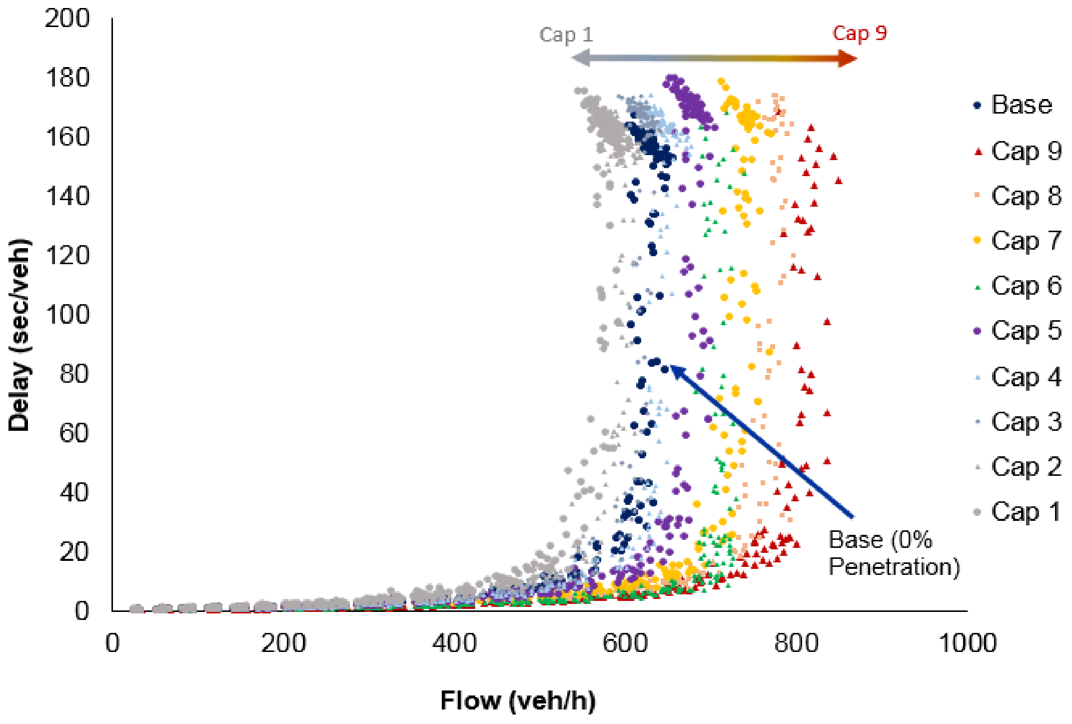
D.4.2. 50% Penetration

Average network delay



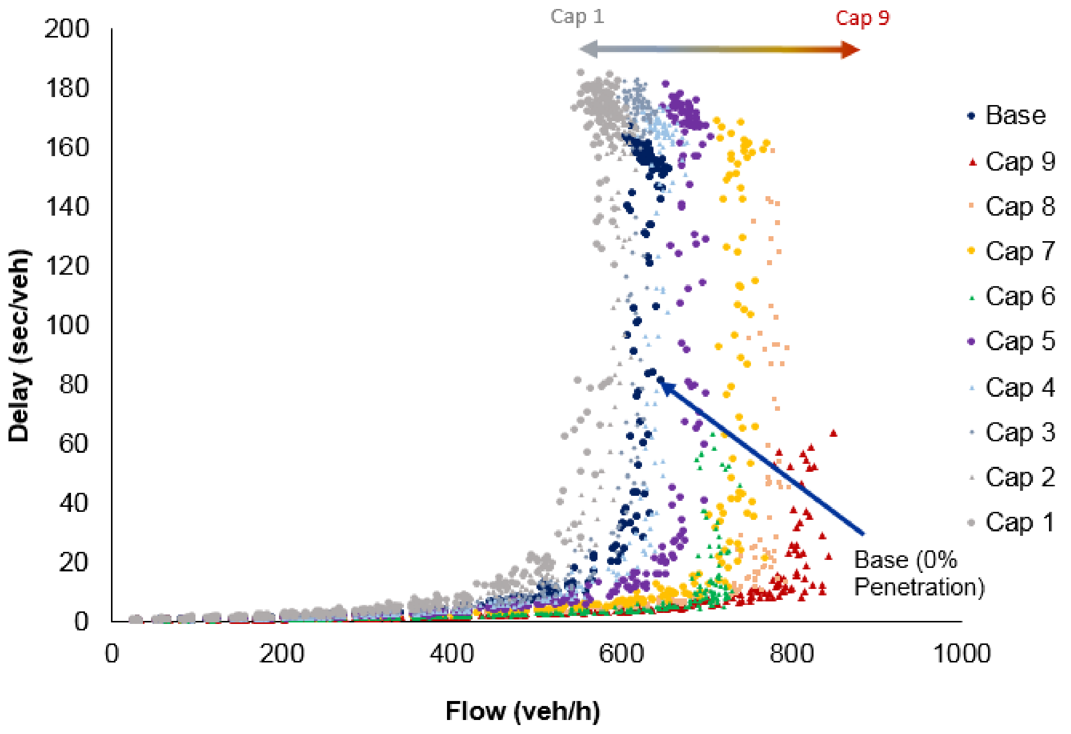
D.4.3. 75% Penetration

Average network delay



D.4.4. 100% Penetration

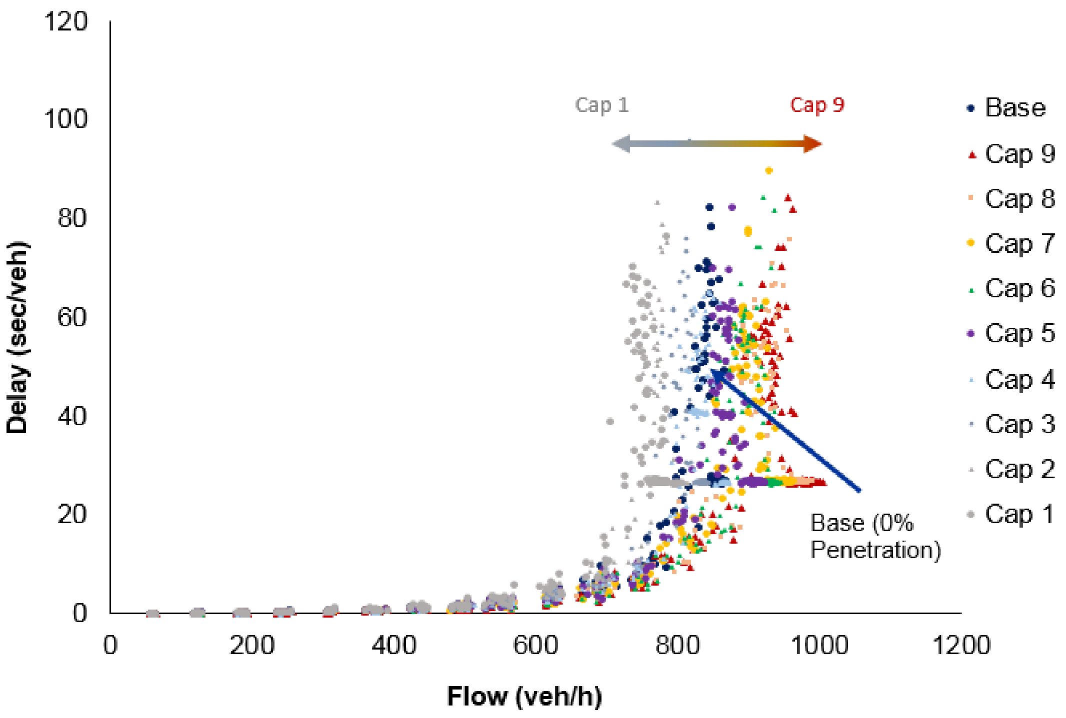
Average network delay



D.5. Model E (multi-lane link with merge)

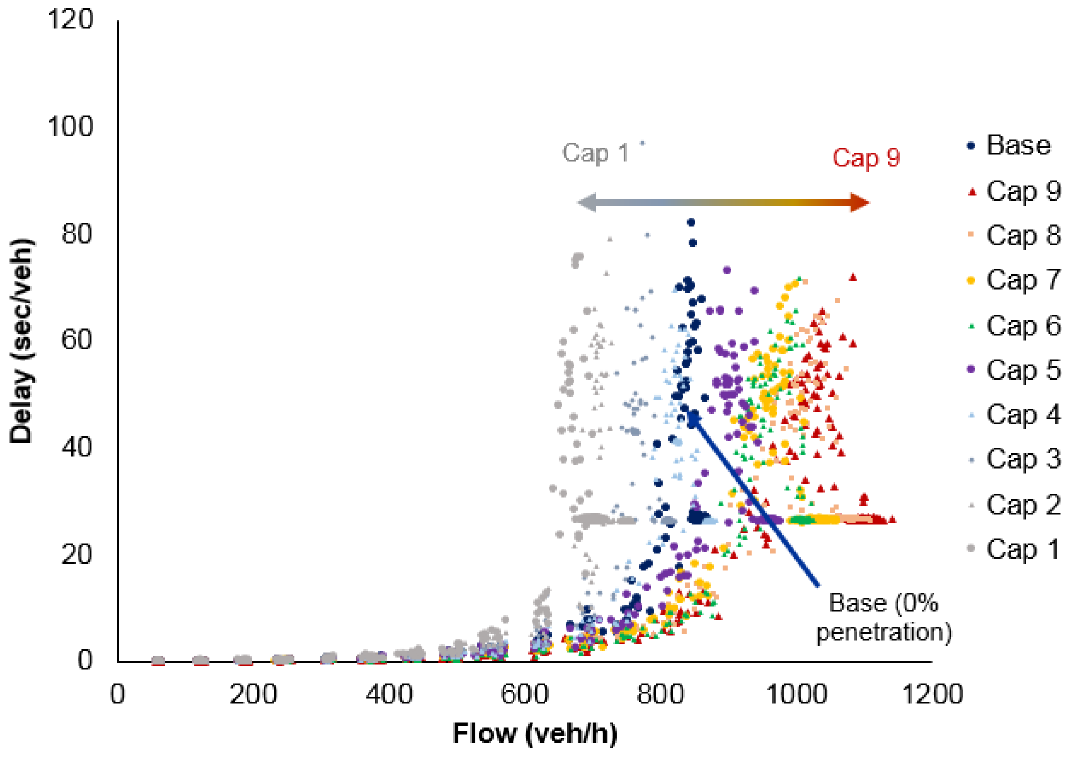
D.5.1. 25% Penetration

Average network delay



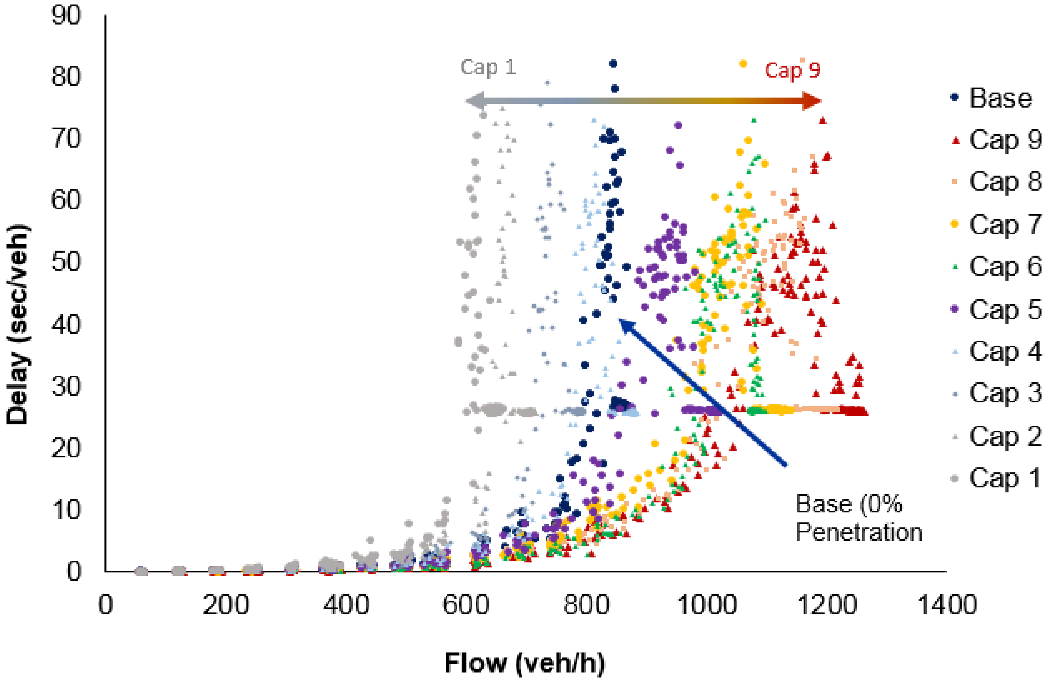
D.5.2. 50% Penetration

Average network delay



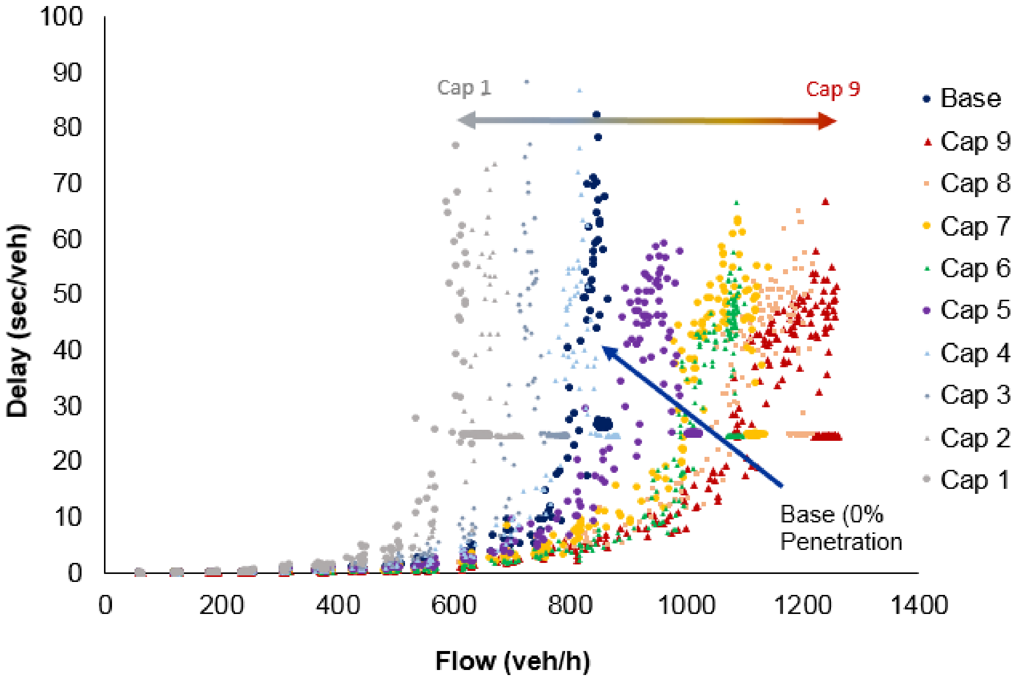
D.5.3. 75% Penetration

Average network delay



D.5.4. 100% Penetration

Average network delay

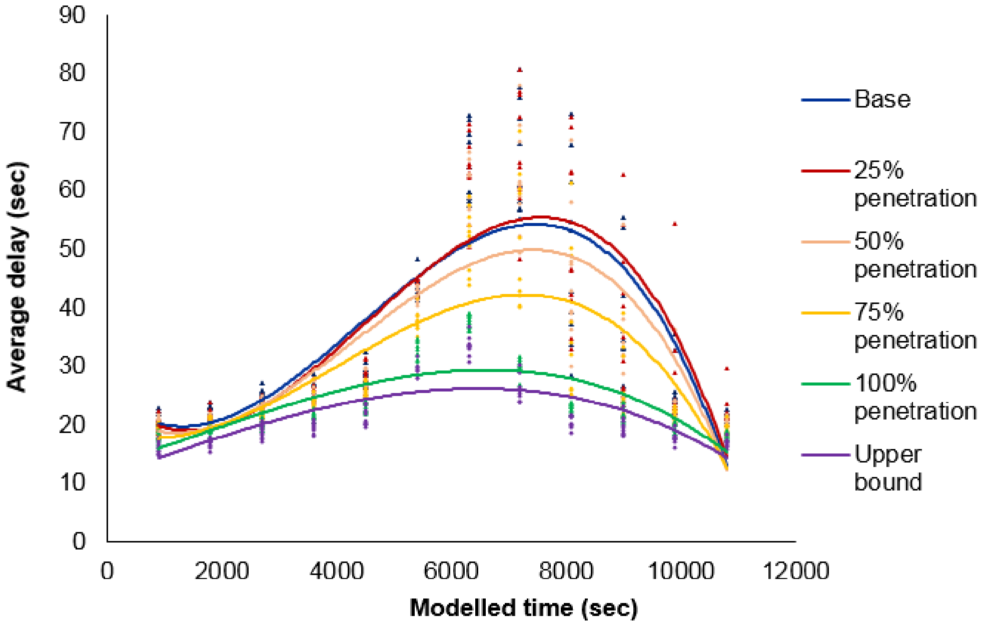


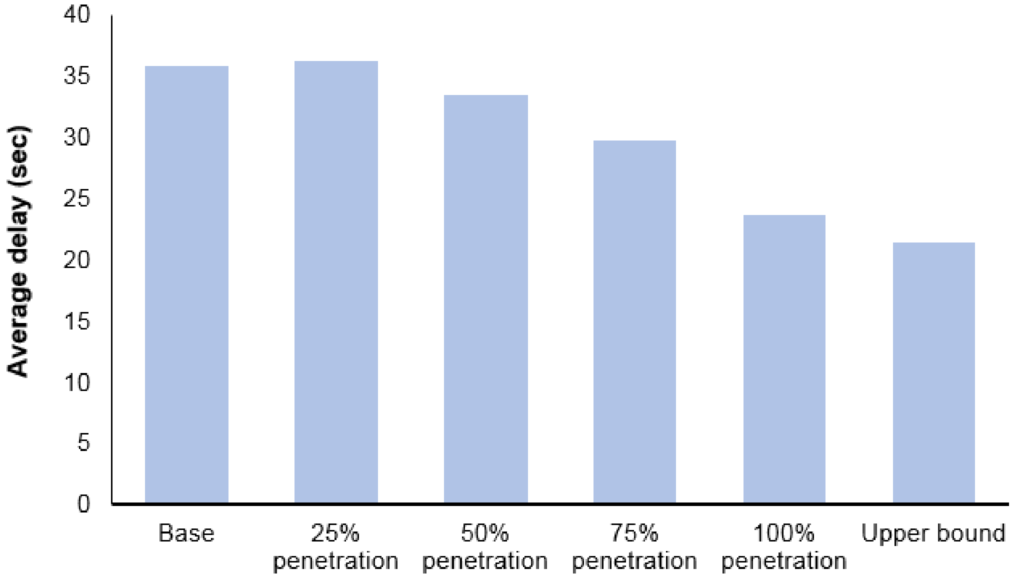
Appendix E. Complex model result graphs

E.1. Model F SRN model

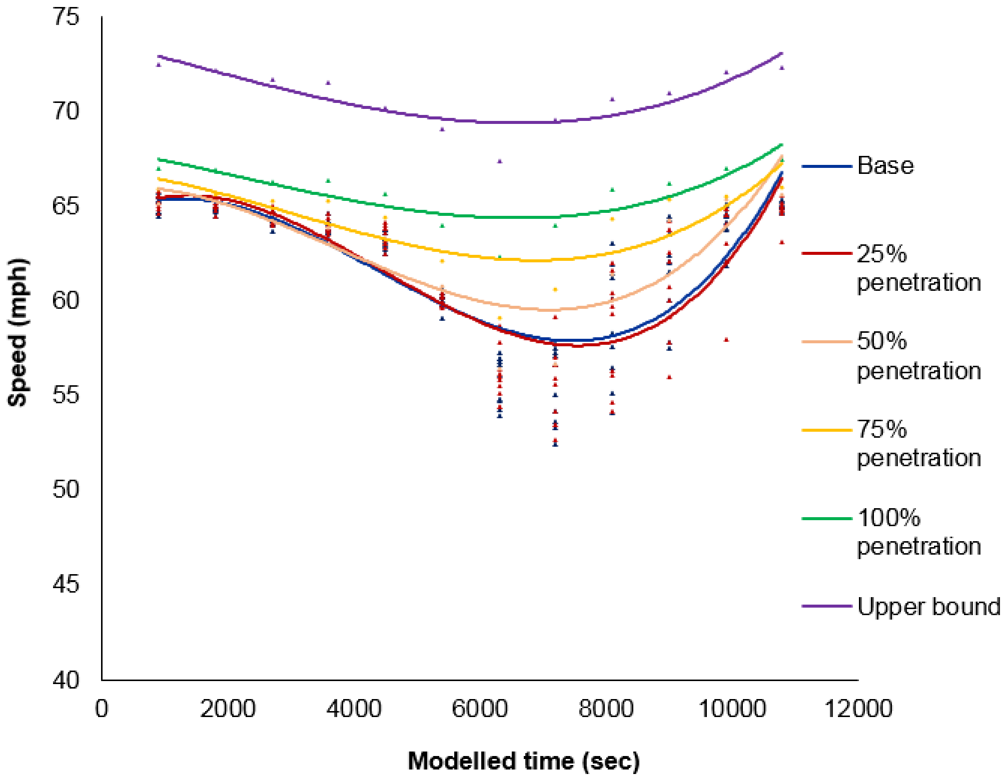
E.1.1. Peak Period

Average network delay

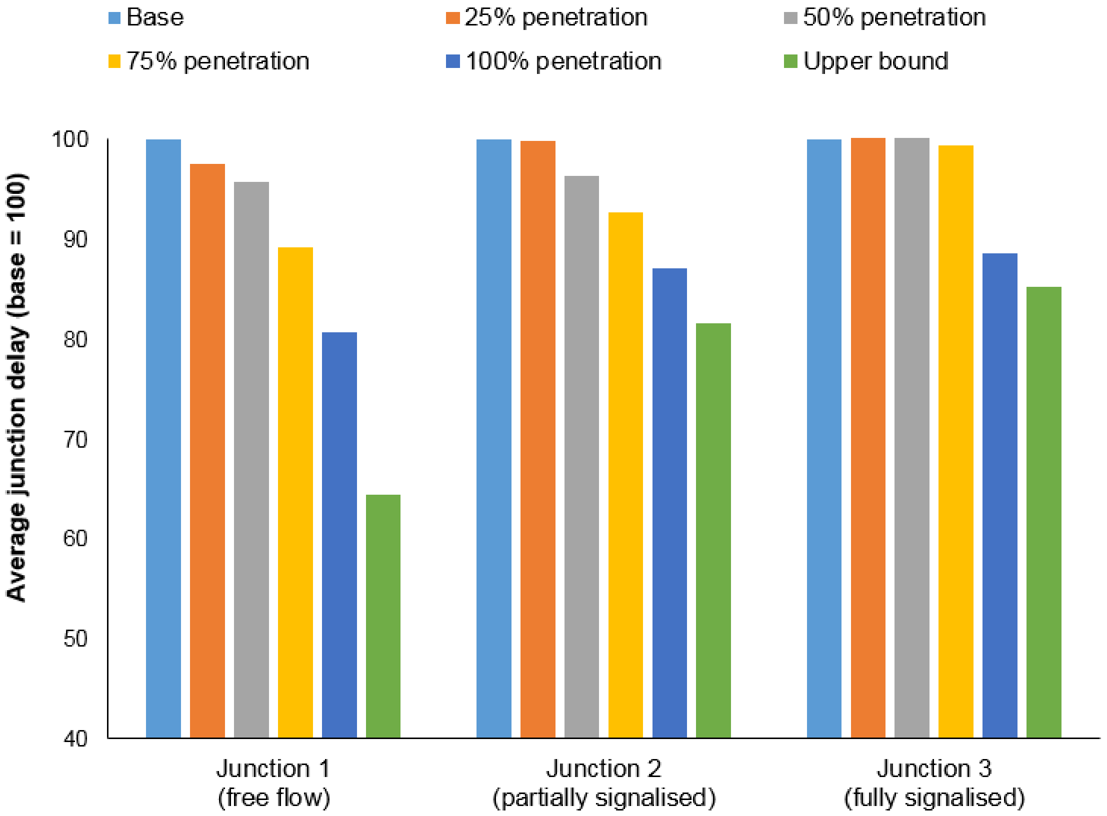




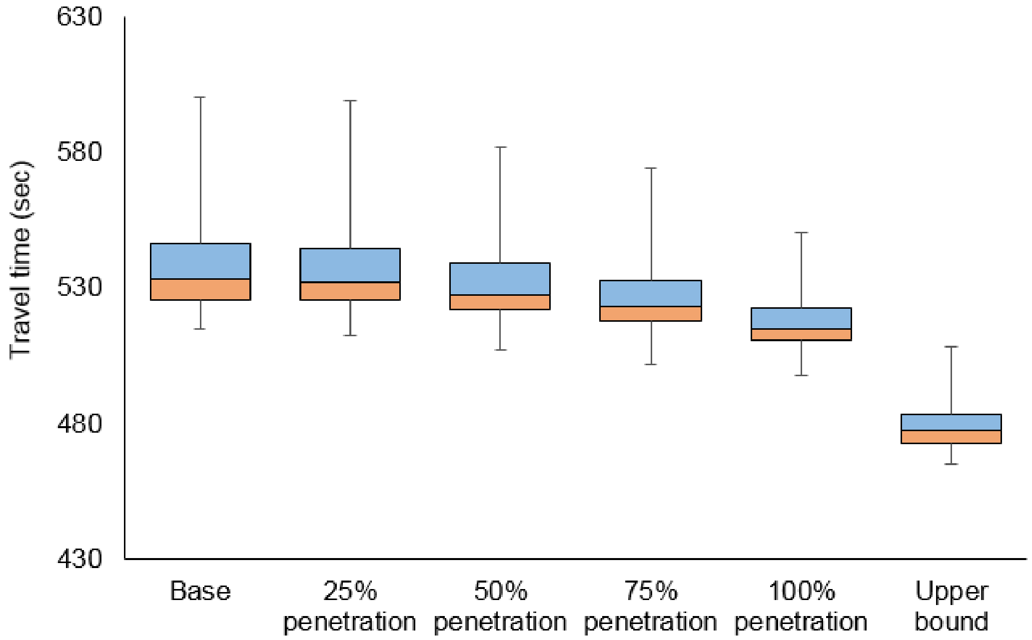
Average network speed

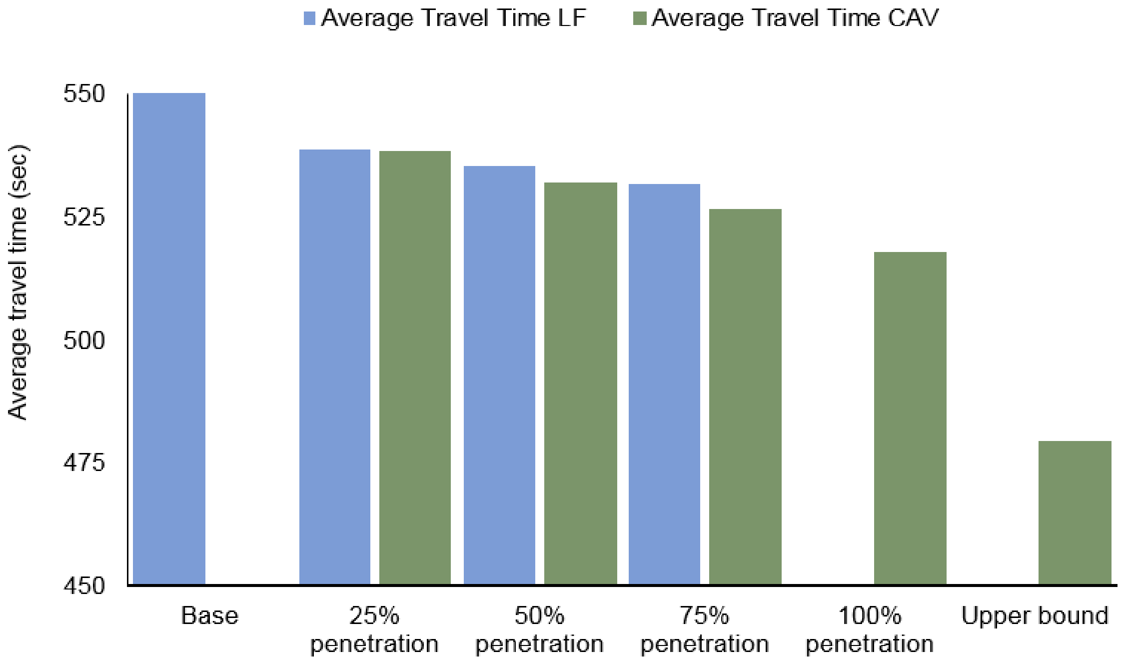


Junction Performance



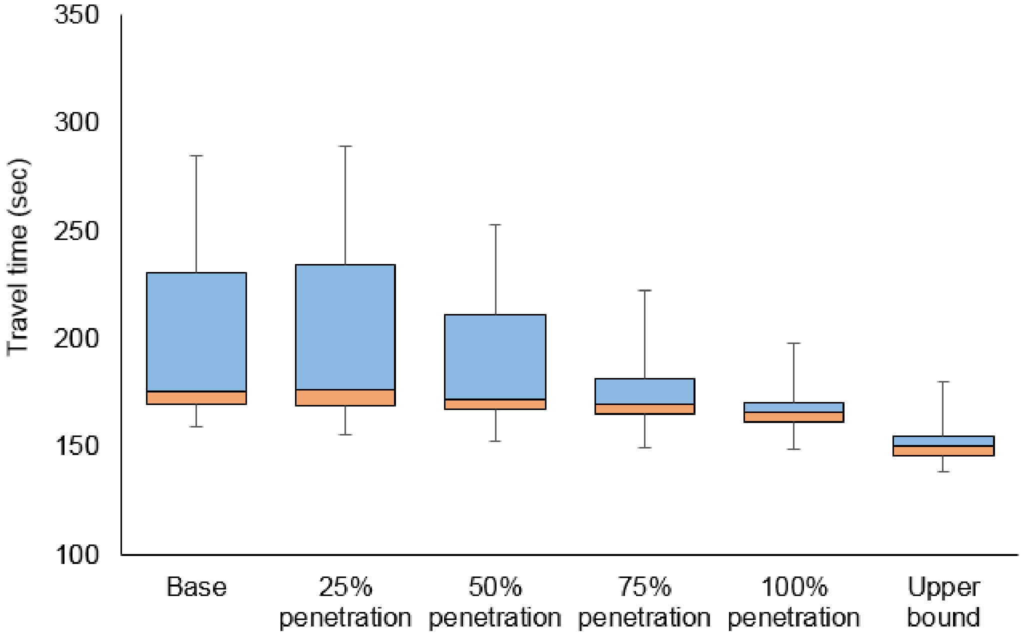
Travel Time JT (segment a)

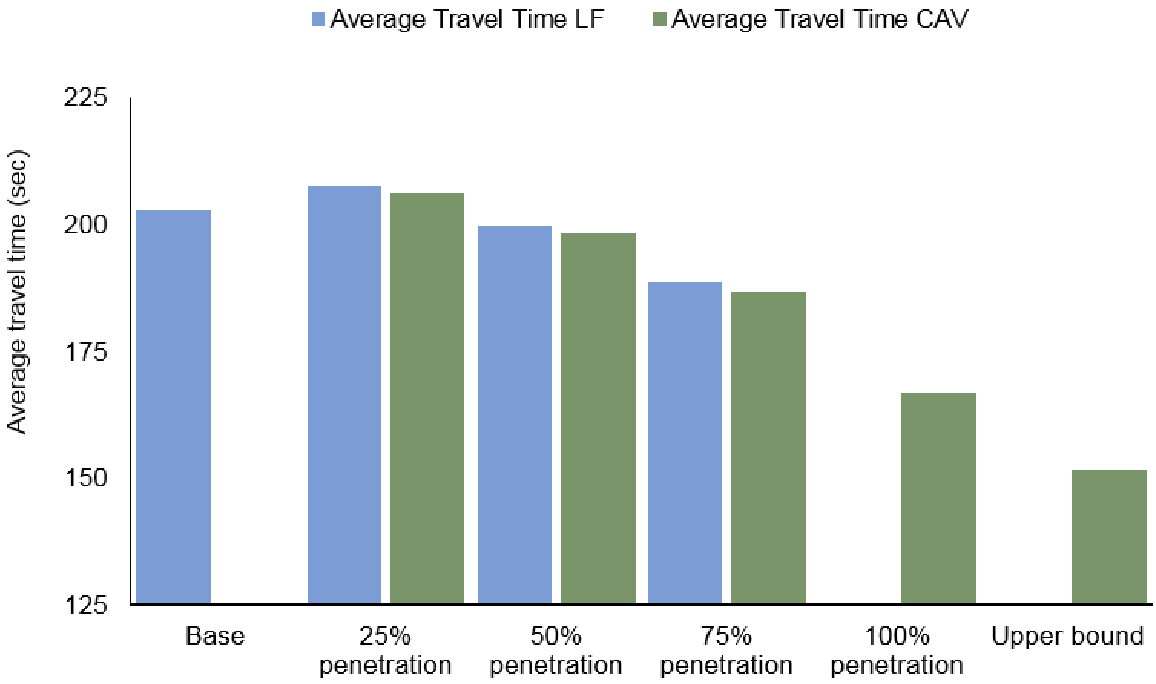




Scenario	Average travel time (s)	Max travel time (s)	Standard deviation (s)	Sample size
All vehicles				
Base	539.8	600.6	20.2	42203
25%	538.5	599.5	19.4	42296
50%	533.6	581.9	17.7	42137
75%	527.7	574.2	15.3	42039
100%	517.8	550.4	10.5	42160
Upper bound	479.3	508.4	9.1	42269
Legacy fleet				
Base	539.8	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

Travel Time JT (segment b)

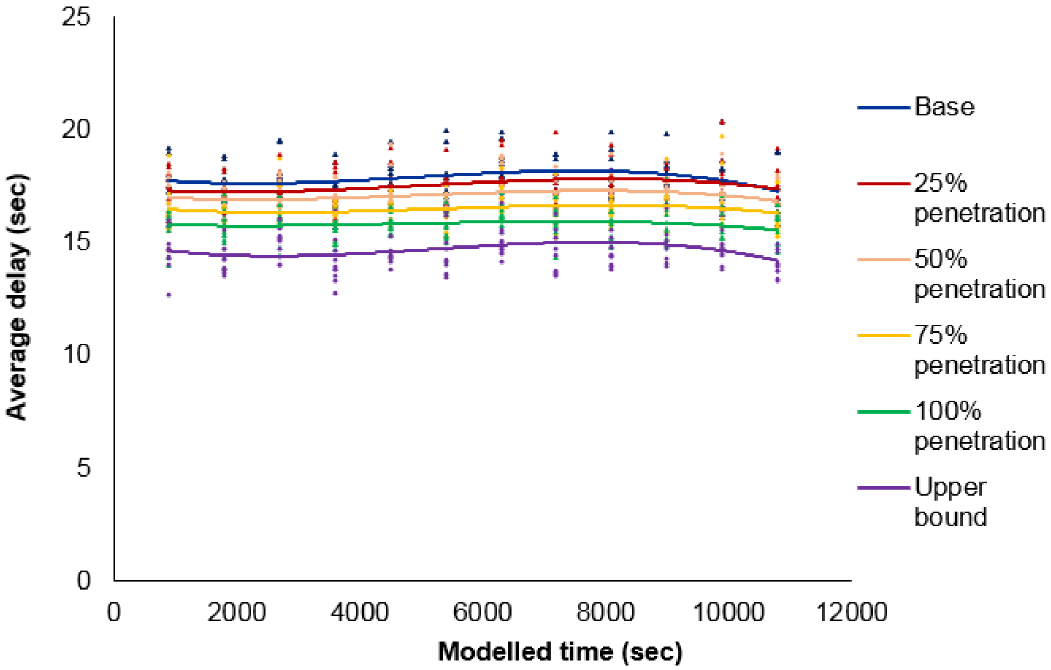


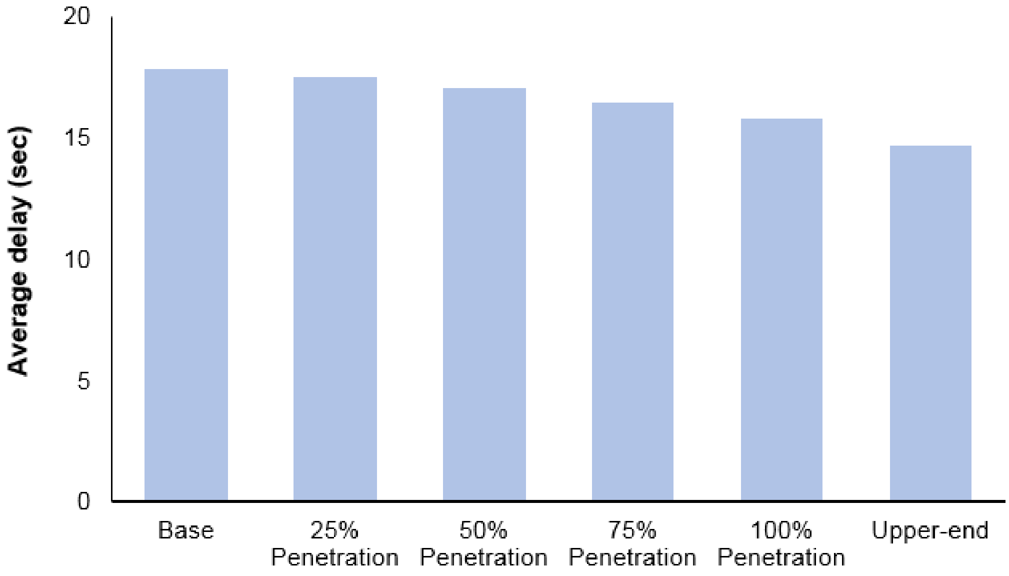


Scenario	Average travel time (s)	Max travel time (s)	Standard deviation (s)	Sample size
All vehicles				
Base	202.8	317.4	50.3	53090
25%	207.1	343.8	55.8	53052
50%	198.9	345.1	51.4	53055
75%	187.2	355.1	42.9	53091
100%	166.6	180.4	6.0	53060
Upper bound	151.5	173.6	6.7	53051
Legacy fleet				
Base	202.8	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

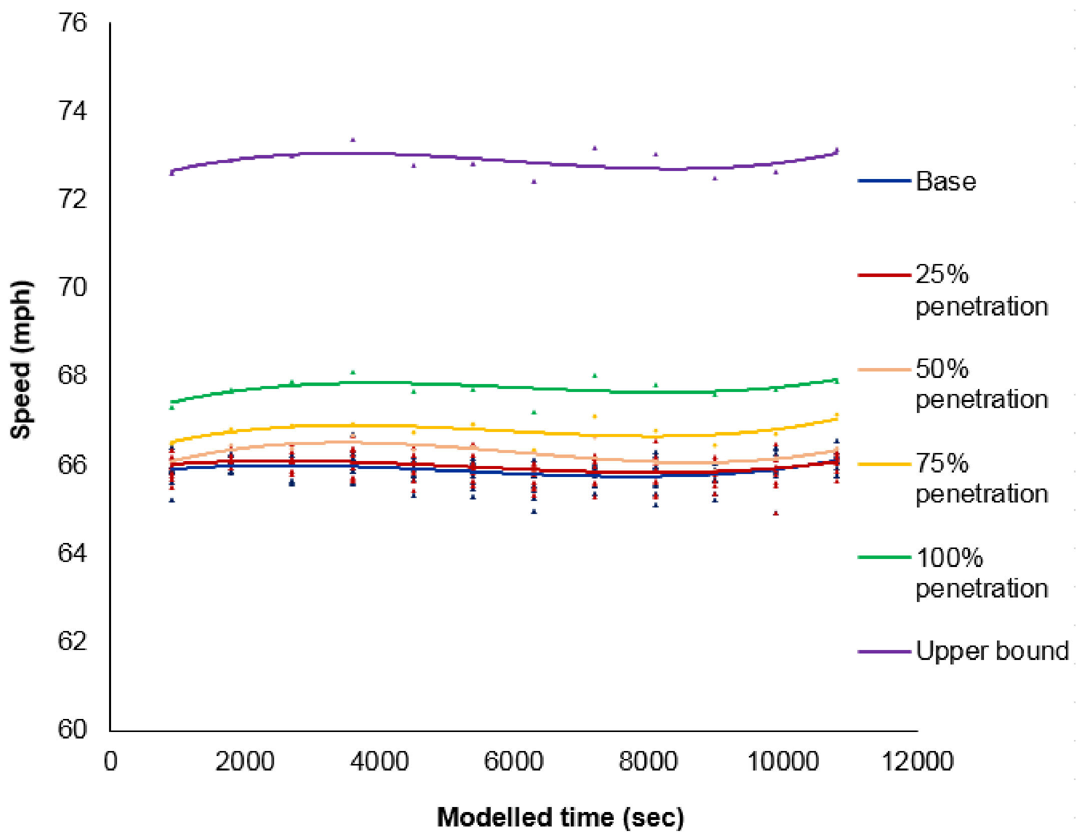
E.1.2. Non-peak Period

Average network delay

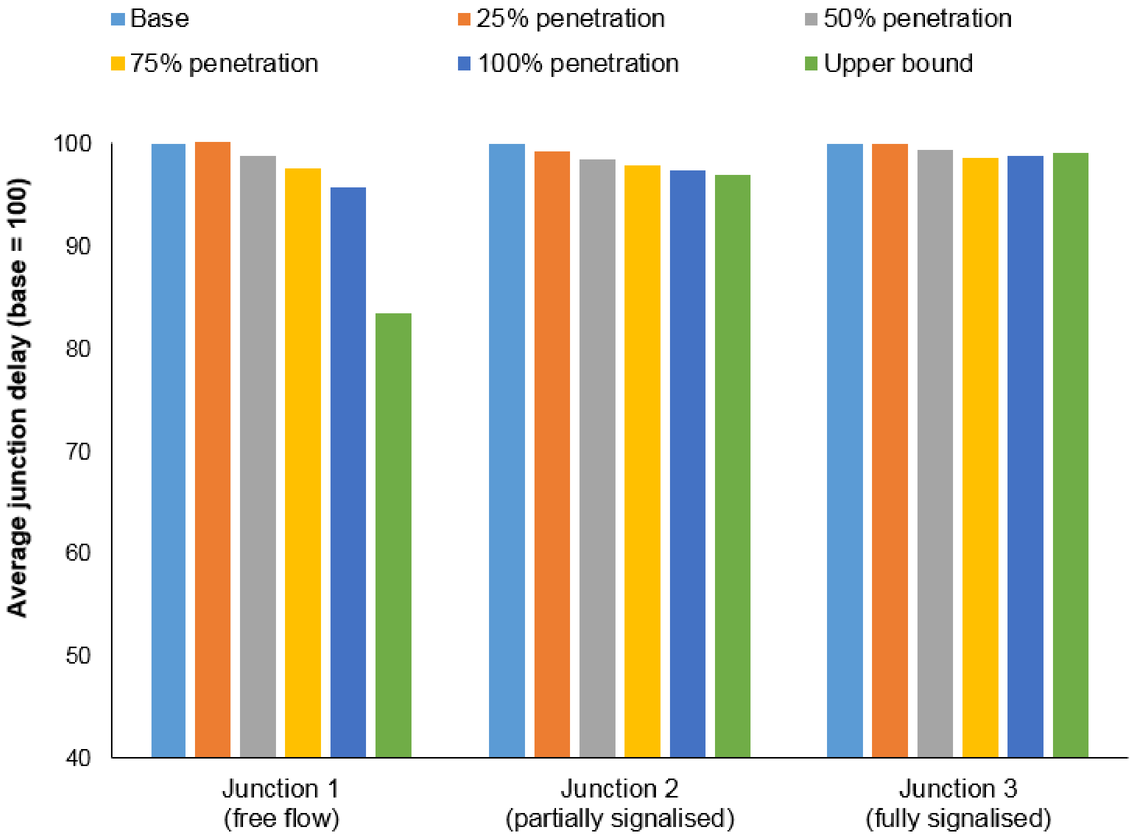




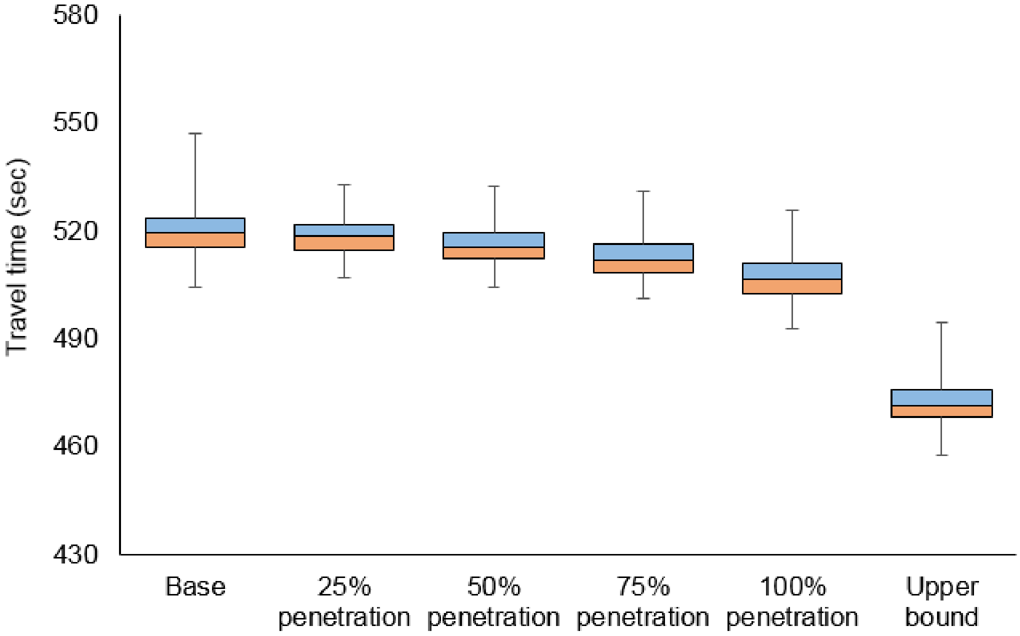
Average network speed

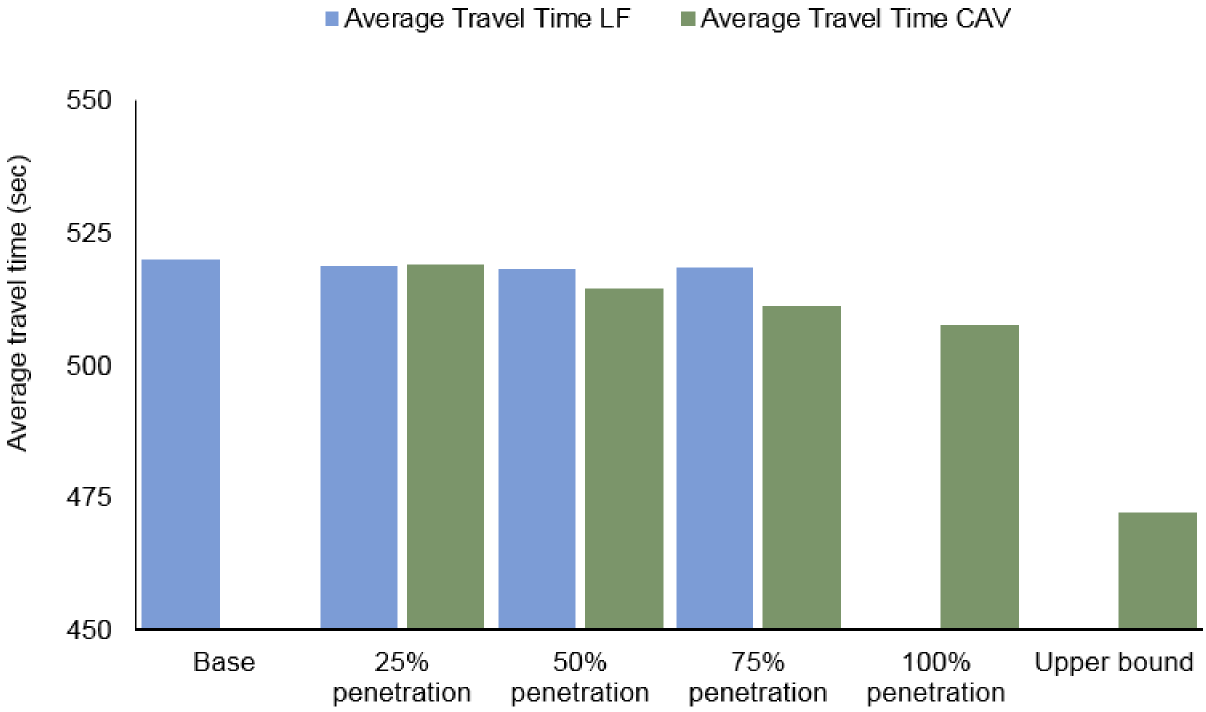


Junction Performance



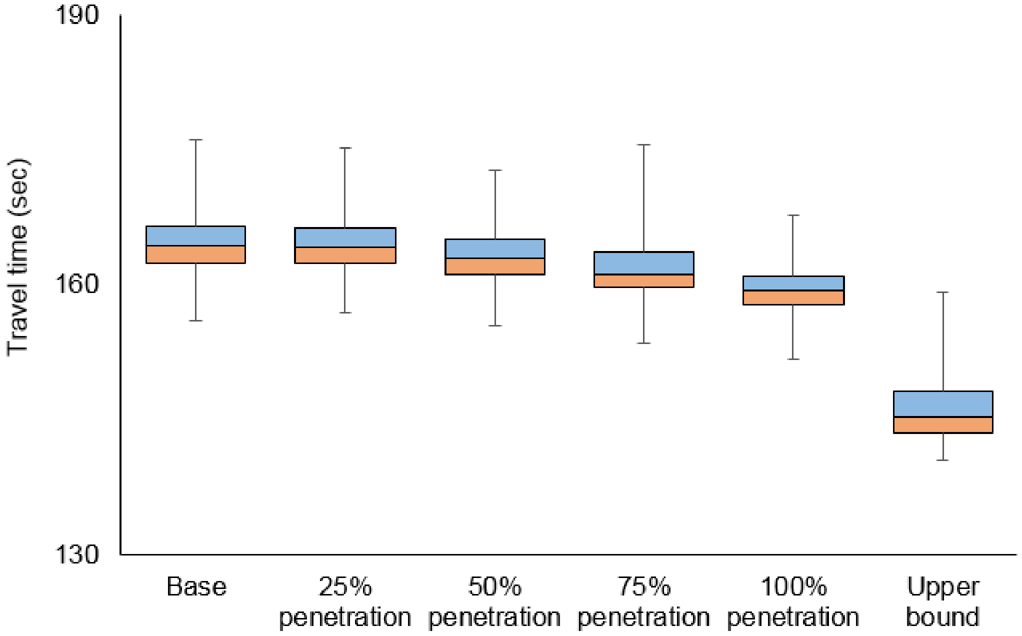
Travel Time JT (segment a)

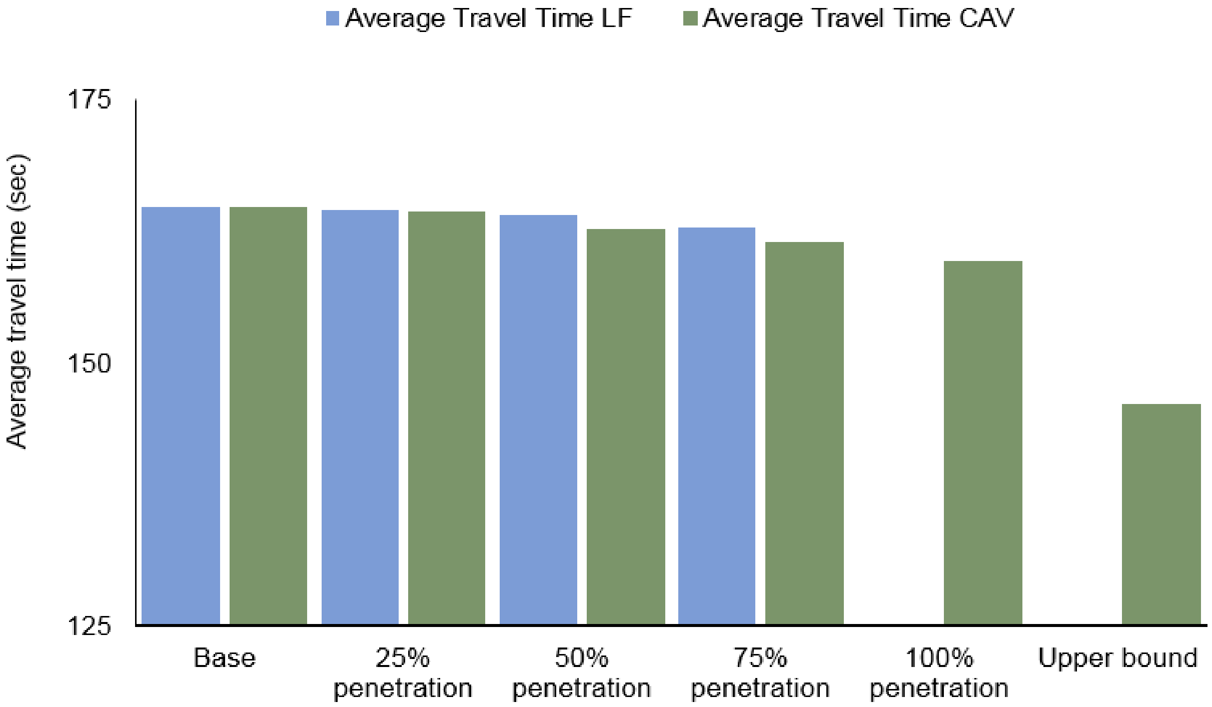




Scenario	Average travel time (s)	Max travel time (s)	Standard deviation (s)	Sample size
All vehicles				
Base	520.0	547.3	6.6	30353
25%	518.7	532.8	5.4	30238
50%	516.2	532.4	5.8	30235
75%	512.8	531.3	5.8	30265
100%	507.3	525.7	6.5	30251
Upper bound	472.1	494.7	6.3	30223
Legacy fleet				
Base	520.0	547.3	6.6	30353
25%	518.6	534.7	5.8	22434
50%	518.1	535.8	6.8	15100
75%	518.2	546.5	10.5	7660
100%	-	-	-	-
Upper bound	-	-	-	-
CAVs				
Base	-	-	-	-
25%	518.9	549.6	12.2	7729
50%	514.4	541.3	9.0	14975
75%	511.0	531.9	7.2	22376
100%	507.3	525.7	6.5	29557
Upper bound	472.1	494.7	6.3	30223

Travel Time JT (segment b)



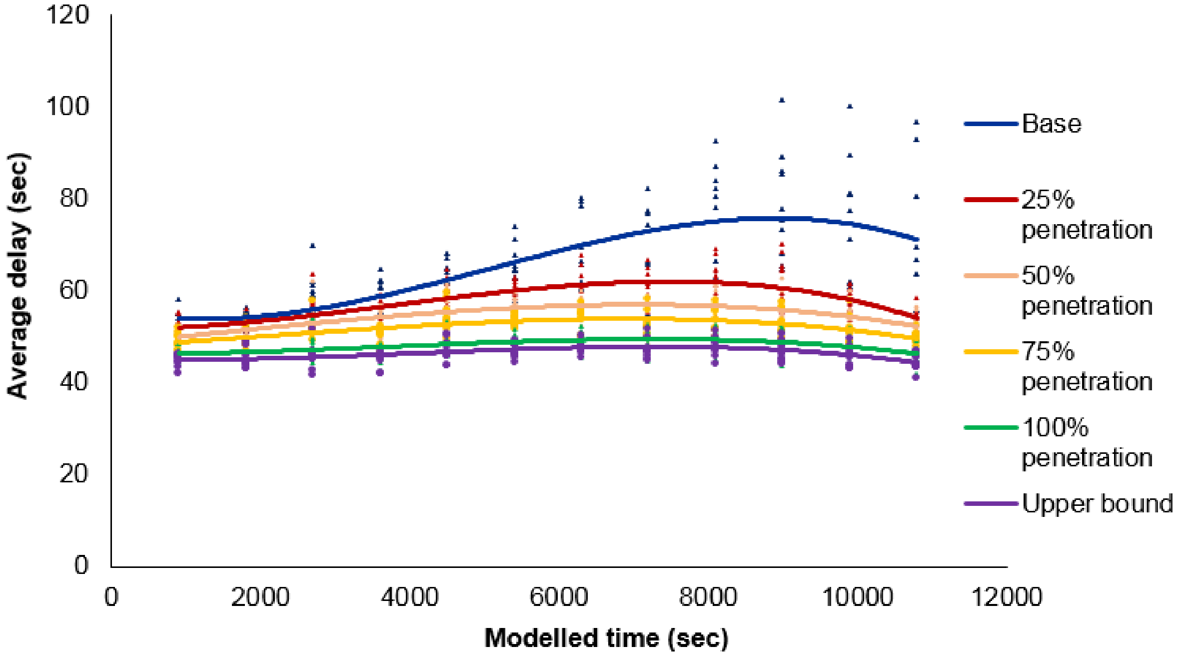


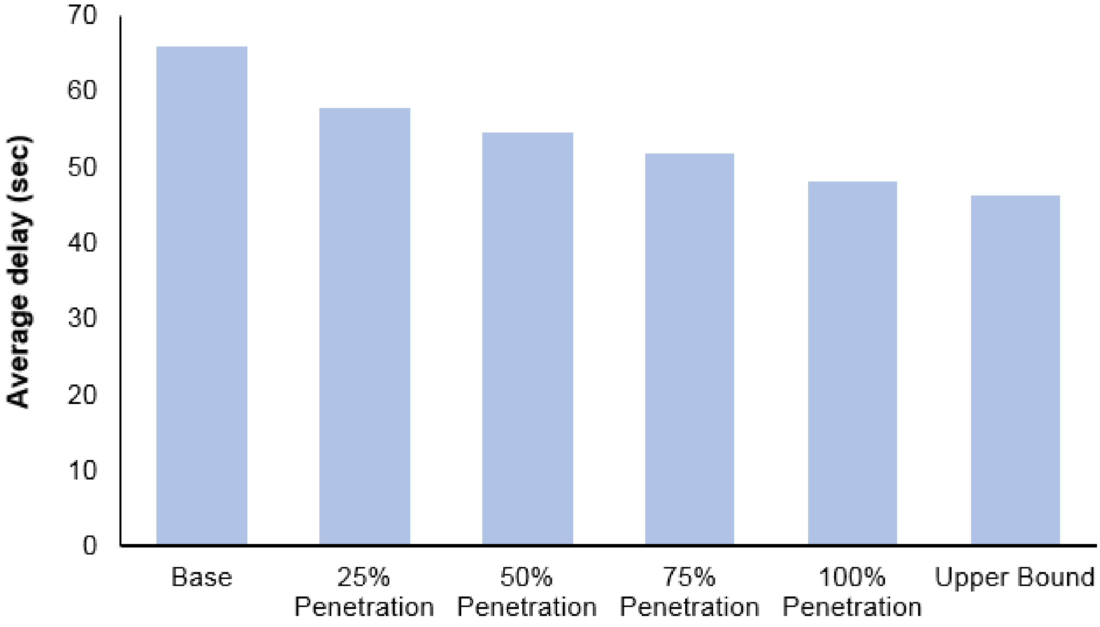
Scenario	Average travel time (s)	Max travel time (s)	Standard deviation (s)	Sample size
All vehicles				
Base	164.8	176.2	3.4	37861
25%	164.4	175.3	3.0	37834
50%	163.3	172.7	3.2	37849
75%	161.8	175.7	3.2	37841
100%	159.6	167.7	2.9	37849
Upper bound	146.1	159.2	3.5	37856
Legacy fleet				
Base	164.8	176.2	3.4	37861
25%	164.5	174.3	3.0	28187
50%	163.9	173.0	3.1	18804
75%	162.7	176.2	3.3	9469
100%	-	-	-	-
Upper bound	-	-	-	-
CAVs				
Base	-	-	-	-
25%	164.3	178.4	4.2	9556
50%	162.7	174.0	3.7	18858
75%	161.4	175.5	3.5	28093
100%	159.6	167.7	2.9	36931
Upper bound	146.1	159.2	3.5	37856

E.2. Model G urban model

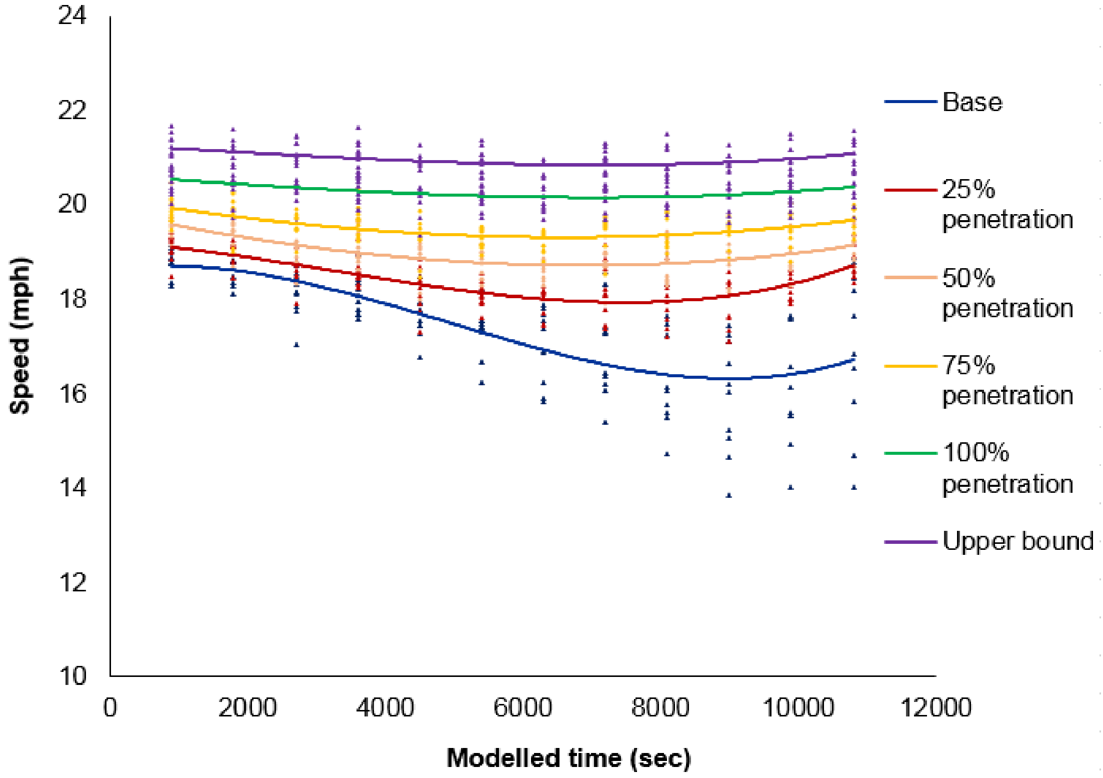
E.2.1. Peak Period

Average network delay

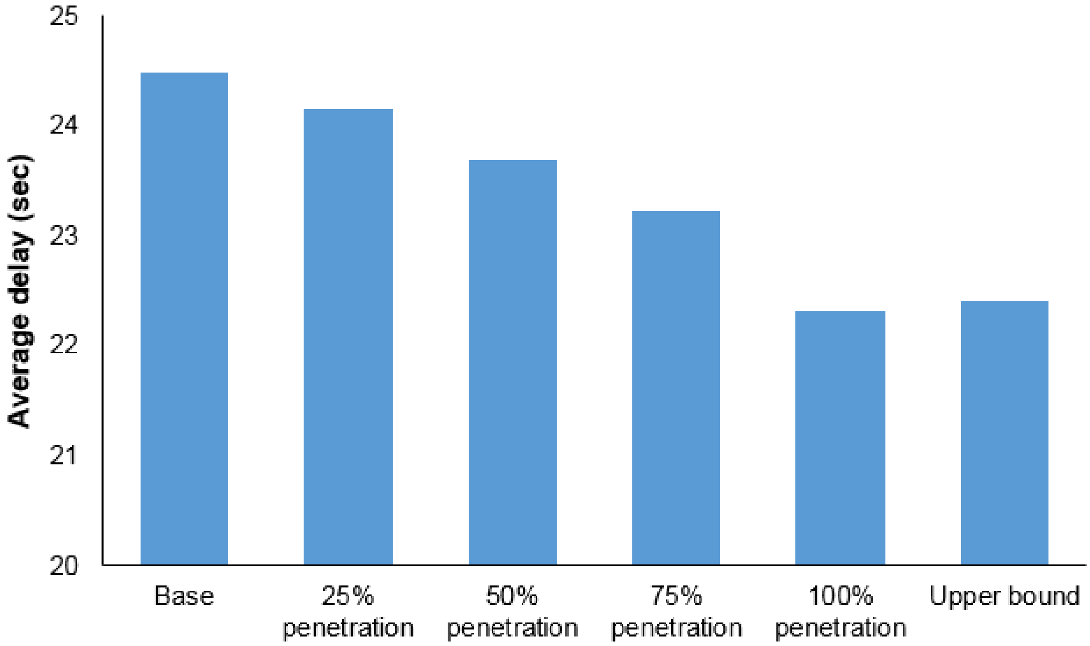




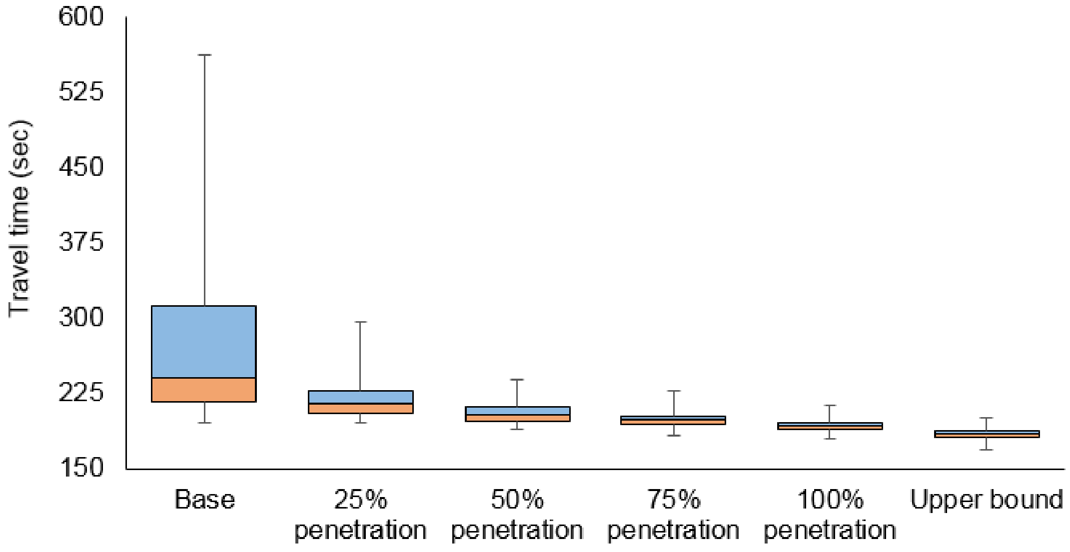
Average network speed

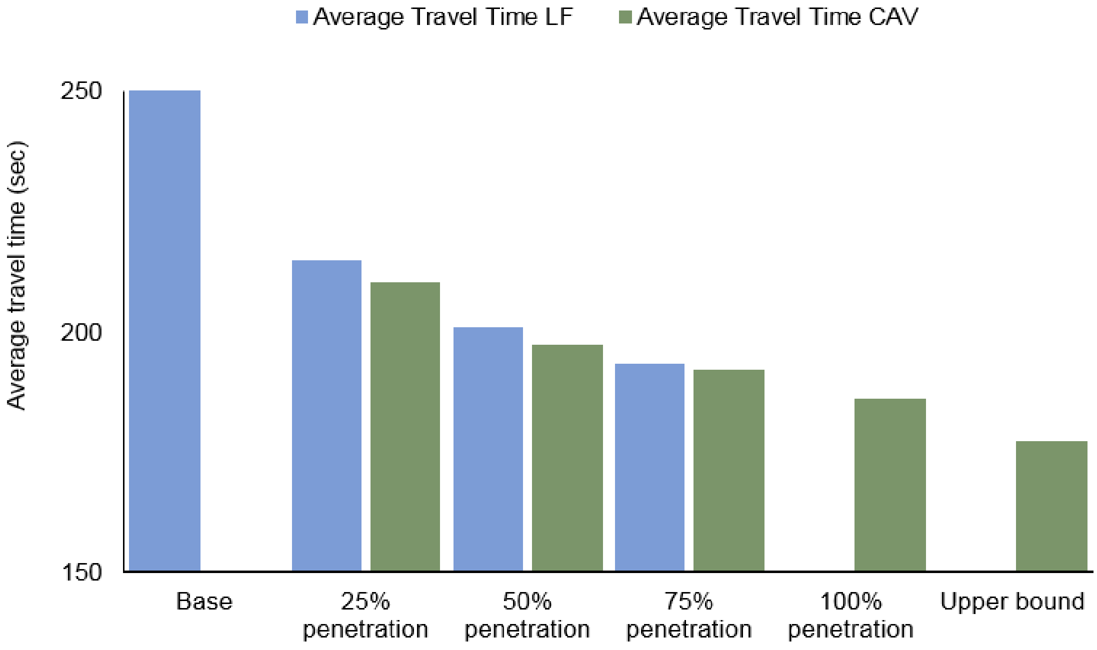


Junction Performance



Travel Time

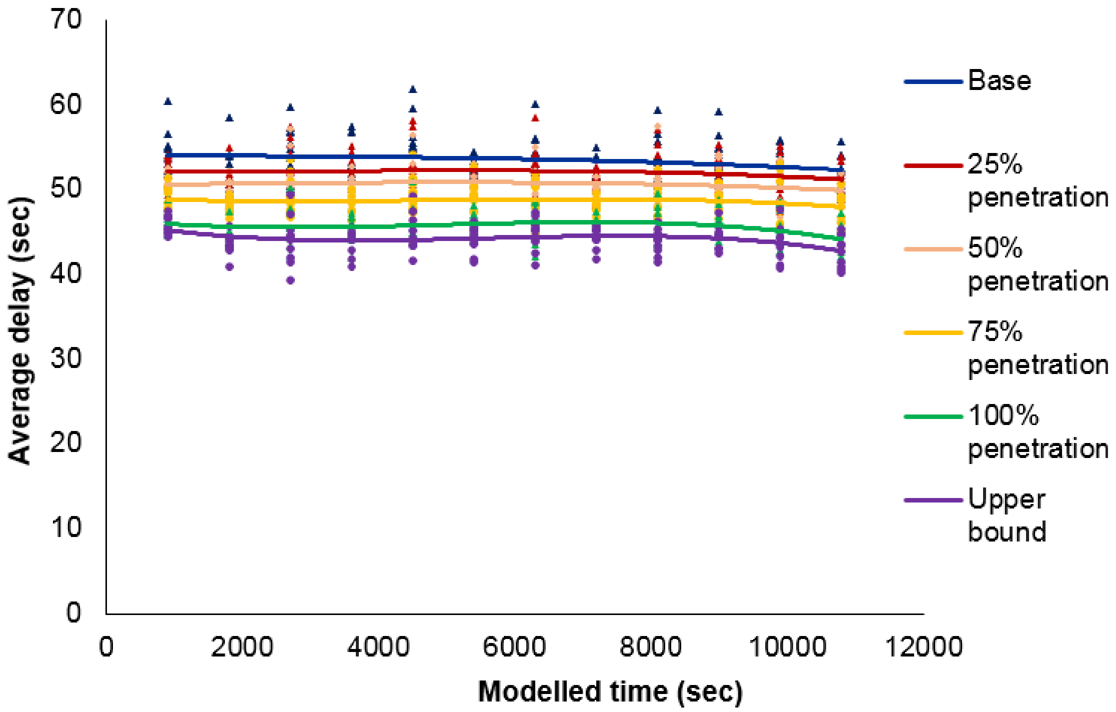

Travel time (sec)
600
525
450
375
300
225
150
Base
25% penetration
50% penetration
75% penetration
100% penetration
Upper bound

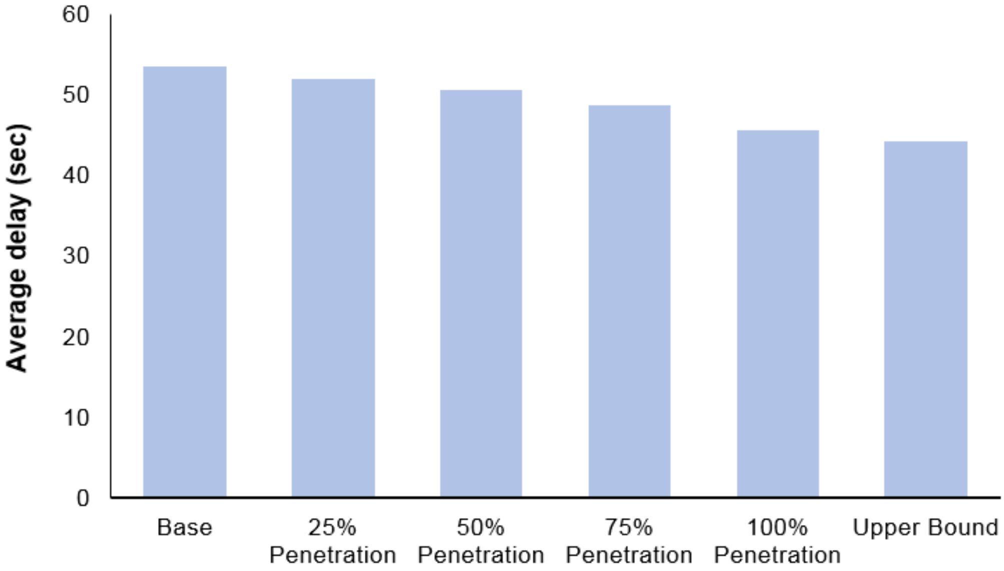

Average Travel Time LF
Average Travel Time CAV
Average travel time (sec)
250
200
150
Base
25% penetration
50% penetration
75% penetration
100% penetration
Upper bound

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

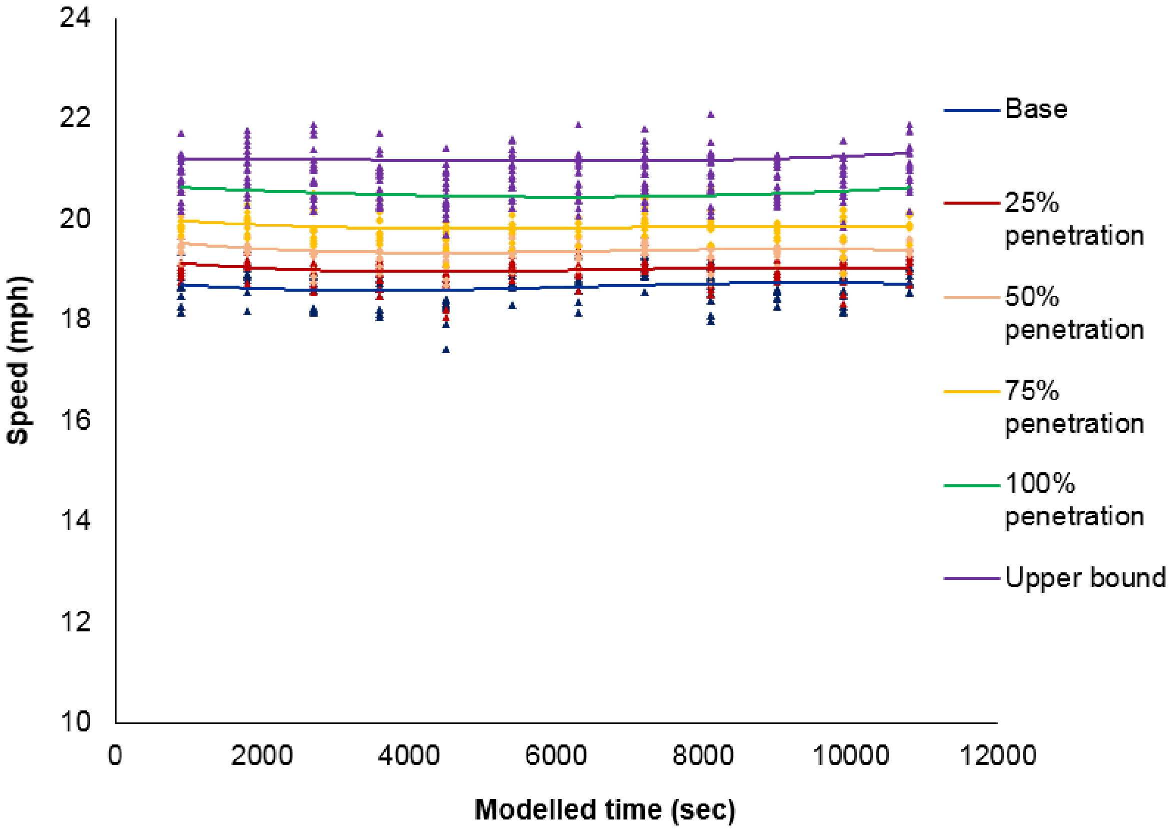
E.2.2. Non-peak Period

Average network delay

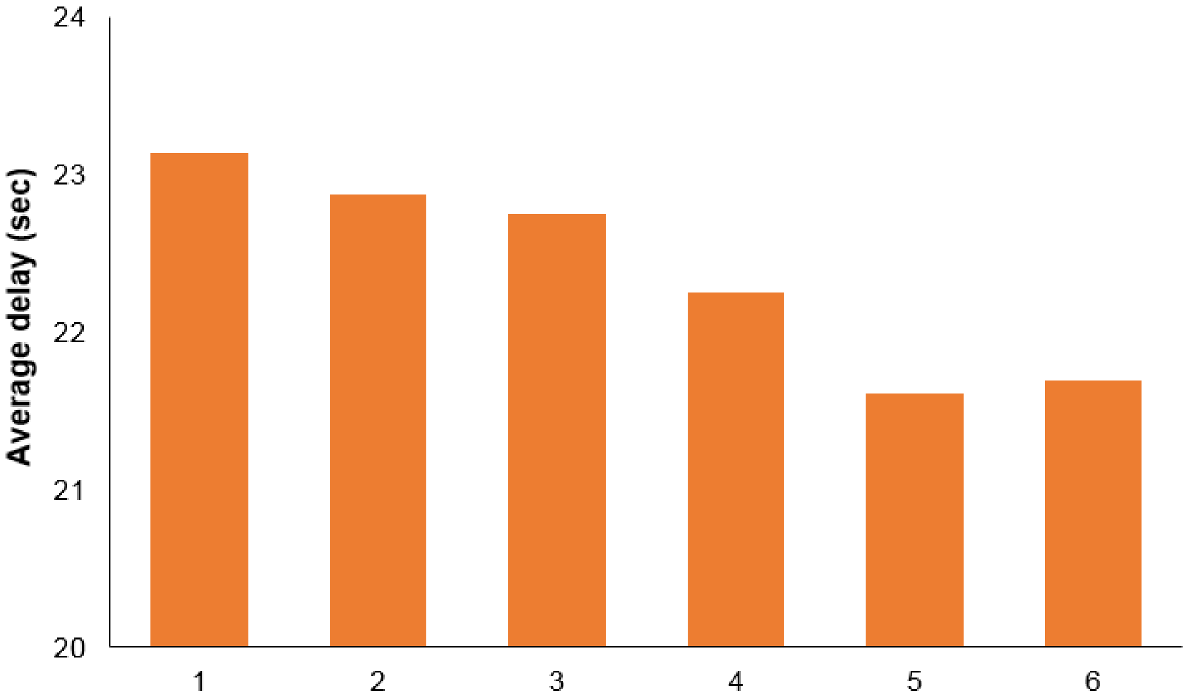




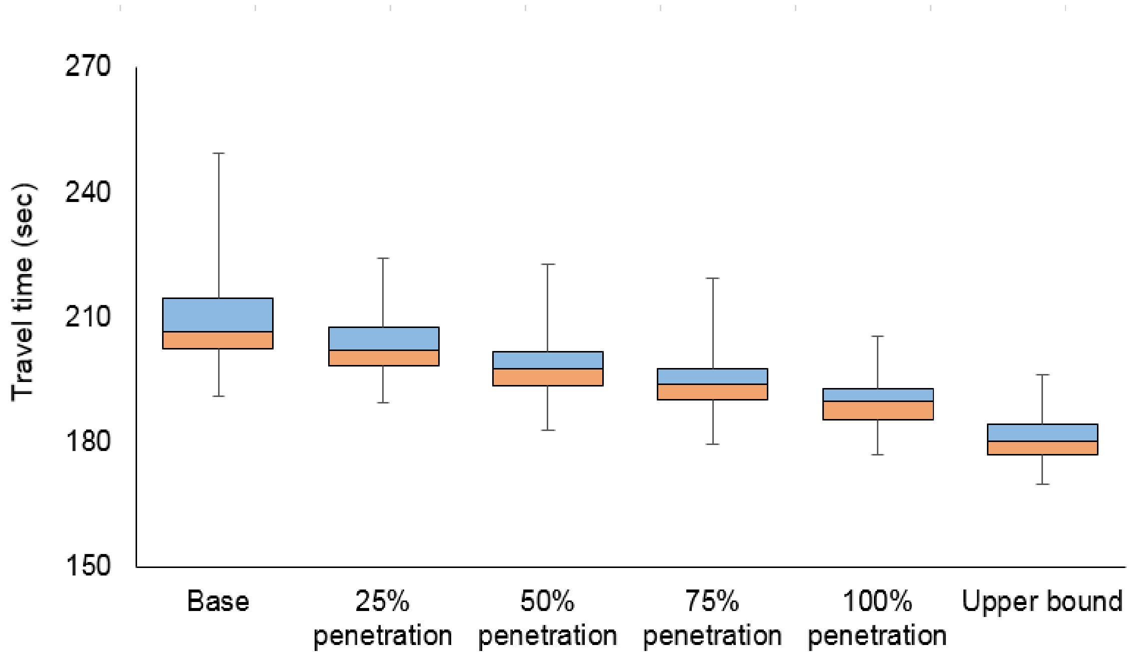
Average network speed

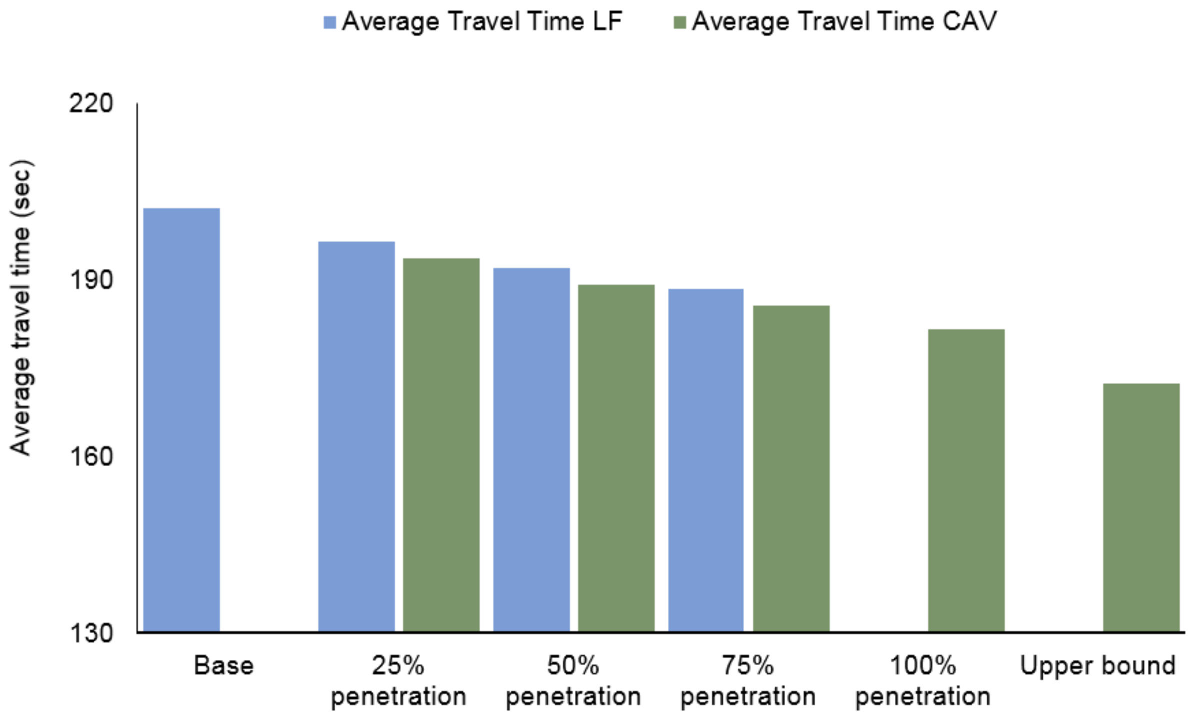


Junction Performance



Travel Time JT





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All vehicles				
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25%	518.7	532.8	5.4	30238
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Upper bound	472.1	494.7	6.3	30223
Legacy fleet				
Base	520.0	547.3	6.6	30353
25%	518.6	534.7	5.8	22434
50%	518.1	535.8	6.8	15100
75%	518.2	546.5	10.5	7660
100%	-	-	-	-
Upper bound	-	-	-	-
CAVs				
Base	-	-	-	-
25%	518.9	549.6	12.2	7729
50%	514.4	541.3	9.0	14975
75%	511.0	531.9	7.2	22376
100%	507.3	525.7	6.5	29557
Upper bound	472.1	494.7	6.3	30223