EXPLORATORY ANALYSIS OF CONNECTED FULLY AUTONOMOUS VEHICLES ON THE SAFETY AND EFFICIENCY OF ROAD NETWORKS USING MICROSIMULATION

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ABSTRACT

The research had set out to explore the effects of the widespread introduction of driverless technology by using publicly available data and assessing the changes it brings to the efficiency and safety of the road network.

ConFAVs were slowly introduced to the network and average vehicle delays and the level of service (LOS) of links observed, followed by a surrogate safety assessment.

Two published behaviour models (Atkins and CoEXist), and a third model (Tested Logic) was created, which accounted for a change in ConFAV behaviour while following another ConFAV. A comparison of the change in the average vehicle delay and the total number of serious conflicts recorded, highlighted that the CoEXist behavioural model had performed the best in three types of junctions and was used to further analyse the case study.

The case study involved 2 small, isolated networks within the Queen Elizabeth Olympic Park Area of London (‘Site A’ was residential and ‘Site B’ was commercial). ‘Site A’ performed well with delays but performed poorly when comparing the number of recorded conflicts against the increasing numbers of ConFAVs. ‘Site B’ showed limited improvement in LOS and performed poorly in the safety analysis as the number of recorded conflicts increased fourfold in some scenarios.

The results of the case study led to a conclusion that increased numbers of ConFAVs driving in platoons within the network could reduce delays and as a result either maintained the LOS of the chosen route or made it better. The lead vehicle in the platoon was able to anticipate changes in signals and communicate this with the trailing vehicles, allowing them to perform better at signalised junctions. Platoons also increased network capacity on congested links allowing better performance in the average delays, as observed in Case Study B. However, greater numbers of platoons resulted in larger numbers of rear-end conflicts when a surrogate safety analysis was performed using Time to Collision (TTC) as a parameter. Thus, it was recommended that another method is used to investigate potential conflicts that could recognise and account for platoons.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DEFINITION OF KEY TERMINOLOGY

This section was written to list the key terminologies used throughout the report, as the terms may vary from the commonly understood definitions. Some terms are accompanied by abbreviations in bracket, and are listed in alphabetical order as follows:

i. ***Autonomous Vehicle (AV):*** A self-driving vehicle designed to travel between destinations with or without the navigation of a human operator. This can vary between 5 levels of automation (see appendix B for the Guide to SAE Defined Autonomy Levels)
ii. ***Car to X (C2X):*** The vehicle is communicating with another vehicle or smart infrastructure.
iii. ***Conventional Driver/Vehicle:*** This vehicle is driven by a human operator and is assumed to have 0 level of automation (see appendix B for the Guide to SAE Defined Autonomy Levels)
iv. ***Connected Fully Autonomous Vehicle (ConFAV):*** An autonomous vehicle operating at the highest level of autonomy and requires no input from a human operator, apart from the destination (see appendix B for the Guide to SAE Defined Autonomy Levels). This vehicle is connected with infrastructure and other vehicles through C2X technology.
v. ***Desired Speed:*** If there are no hindrances such as signal controls or other road users, the driver will travel at this speed.
vi. ***Fully Autonomous Vehicle (FAV):*** An autonomous vehicle operating at the highest level of autonomy and requires no input from a human operator, apart from the destination (see appendix B for the Guide to SAE Defined Autonomy Levels).
vii. ***High-Speed Rail (HSR):*** This is a form of rail transportation that is achieves significantly higher velocity than the traditional rail car.
viii. ***Infrastructure to Vehicle (I2V) Communication:*** This is when the vehicle is communicating with its surrounding infrastructure to inform its decision making.
ix. ***Inter-infrastructure (I2I) Communication:*** This is when the infrastructure managing a network, sends and receives information among each other.

x. ***Level of Service (LOS):*** This determines the level of delays experienced on a road network and is indicated from A (the best service) to F (the worst).

xi. ***Light Rail Transit (LRT):*** This is an urban form of rail that operates faster and at a higher capacity than a tram, whilst using similar infrastructure to a tramway with right-of-way.

xii. ***Motorway:*** A dual carriageway that is designed for higher speeds but has very few entries and exit points.

xiii. ***Network Demand:*** The number of vehicles (usually measures per hour) that will be travelling along the network.

xiv. ***Relative Flow:*** This shows the division of the number of vehicles travelling along a link among various vehicle types.

xv. ***Vehicle Composition:*** The different types of vehicles that make up the traffic in a road network.

xvi. ***Vehicle to Vehicle (V2V) Communication:*** Communication between similarly equipped vehicles, facilitating decision making.

xvii. ***Vehicle to Infrastructure (V2I) Communication:*** Vehicles communicating with smart infrastructure to facilitate decision making.

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DEDICATION

"I dedicate this thesis wholeheartedly to my mum Gloria, my role model, my teacher, the strongest woman I know, and whom I strive daily to make her proud of my achievements."

1. INTRODUCTION

1.1 Scope of Research

This research aims to investigate the potential effects of the widespread use of connected fully autonomous vehicles (ConFAVs) on the congested urban landscape, by exploring the potential driving behaviour of these ConFAVs and how they may potentially impact the level of service and safety on our network of roads.

For the purpose of this study, ConFAVs are defined as SAE Level 5 (full automation) according to the SAE international J3016TM “Levels of Driving Automation” standard, where the automated driving system (ADS) is capable of operating the vehicle on-road anywhere within its region of the world under all road conditions in which a conventional vehicle (SAE Level 0) can be reasonably operated by a typically skilled human driver. The vehicles in the research are classed as “connected” as they have the capability of communication with each other and road infrastructure.

1.2 Introduction to Research Context

The existence and continued growth of several megacities worldwide are the result of rapid urbanisation due to a growing global population and economy. Data from the United Nations indicate that half of the world’s population, an estimated 3.5 billion people live in cities today, and according to the World Health Organisation (WHO), by 2050,7 out of every 10 people in the world will be living in urban areas (TRL, n.d.). Rapid urbanisation sees London, among the most populated Urban cities of the world, as the highest populated city in the UK, with an estimated 8.77 million residents according to a Statistical bulletin by the Office of National Statistics (ONS, 2018). This estimate does not include the thousands that travel from the suburbs to the Capital for work on a daily basis (Office for National Statistics, 2013), making congestion intolerable during peak travel times.

It can be argued that suitable mobility and transportation can form the backbone of any prosperous city, as it is linked to every other industrial sector (VDA Magazine, 2015). In fact, the UN 2030 plan has identified sustainable transport as “essential” to achieving its 17 development goals.

With the rapid development and imminent deployment of the autonomous there is need to consider the effects these vehicles will have on our congested urban areas. The effects can be broken all the way down to the individual user of the technology. But does this mean that a two-car household can be reduced to a single autonomy level 5-car household? (See Appendix B for the definition of levels) To determine the effects motor-vehicle automation is likely to have on congested road networks and the development of the new urban environments, the following questions may be asked: What levels of automation are acceptable? What are the likely changes to the level of service following full vehicle automation? Will our roads be safe?

1.3 Research Objectives

The research is centred around answering the following three questions:

- How are connected fully autonomous vehicles (ConFAVs) expected to behave within urban road networks?
- What operational impacts can ConFAVs have on the level of service of urban road networks during the transition period (where there is a mix of both conventional and autonomous vehicles) and full automation?
- Are there any associated collision risk factors of ConFAVs within urban road networks?

1.4 Rationale and Significance

Current research indicates that the development of autonomous vehicles is focused on the design of the vehicle and its algorithms, as individual car manufacturers race to release the first level 4/5 vehicle (see appendix B for level definition). The public is regularly engaged, primarily to determine their opinions on the foreseen benefits of owning a FAV, their concerns and reservations about the vehicle, and their willingness to pay for the technology, to establish user demand. However, little is known about the transitional period from zero autonomy to full autonomy on the already congested road network, as these vehicles are tested in small numbers, often one at a time in a controlled environment.

This research had set out to explore the effects of the widespread introduction of driverless technology on the congested urban landscape, by using publicly available information about the technology, and assessing the changes it brings to the level of service and the number of unsafe interactions observed within the network.

1.5 Role of Researcher

As this project was conducted as a requirement for the completion of the researcher's PhD studies, the researcher was responsible for planning and conducting the entire study, with the advice of the members of the supervisory team. All studies and experiments were fully investigated, tested, and validated by the researcher.

1.6 Organisation of the Report

The core of this report has been divided into 7 additional chapters. A literature review was conducted to ascertain the state of the Art of the technology before the investigation of its impact on the transportation network. The methodology for the microsimulation model was presented in detail, and the driving behaviour model of the ConFAV tested and applied in a case study. The report is then wrapped up with the conclusions and recommendation chapter. A brief outline of the headings are as follows:

- Literature Review
- Methodology
- Modelling Driving Behaviour of the Connected FAV
- Case Study: Connected Favs Operating Within Communities Around the Queen Elizabeth Olympic Park (QEOP), London
- Conclusions and Recommendations

2. LITERATURE REVIEW

2.1 The presence of autonomous vehicle technology

Autonomous technology is already present in today's world, and manufacturers promise that this will soon be made available on the road. The UK Department for Transport (DfT) has projected that cars with advanced driver assistance features will be available in Britain, and AVs are predicted to be on the road from the mid-2020s onwards (Department for Transport et al., 2015). Experts from the US Institute of Electrical and Electronics Engineers estimate that by the year 2040, light duty autonomous vehicles should account for about 75% of fleet penetration on our roads (Begg, 2014).

The public has already accepted the technology in some controlled environments, as driverless trains have been operating in some parts of the world for decades, such examples include Paris, Copenhagen, London, and Barcelona. London's automated lines which include the Victoria, Central, Jubilee and Northern Lines, have been in operation from as far back as 1968. However, they continue to have drivers in the front carriages, to open/close the doors and occasionally control the speed of the train. The Docklands Light Railway (DLR), which is currently operating in East London, is fully automated and has operated without a driver sitting at the helm. In DLR trains, there is only an agent on board to attend to passengers. Also in London, driverless trains operate at Heathrow, Gatwick and Stanstead airports. In 2011, the Heathrow Airport in London launched the first commercial application of an Urban Light Transport (ULTra) System, pictured in Figure 2-1 below, which introduced driverless pods on a 4km guideway that shuttled passengers between a car park and Terminal 5 (Rodrigue, 2020).

Figure 2-1 ULTra System at Heathrow airport (Rodrigue, 2020).

The progression of this research has however raised the question of the subsequent effects the introduction of AVs could have on current city layouts. The question is: whether the operation of autonomous vehicle - which is anticipated as the transportation solution for cities of the future - will only be as efficient as the infrastructure within which it operates. However, during the ICE Roads 2016 conference held on April 20th, 2016, in Westminster, delegates highlighted of the absence of clear infrastructural requirements for the optimum performance of autonomous vehicle on the existing road networks. Neil Fulton, Programme director at Transport Systems Catapult, said the lack of guidelines was due to insufficient testing of such vehicles on the roads. TS Catapult is currently spearheading an Innovate UK-funded programme that will allow their autonomous cars, known as the LUTZ Pathfinder automated pods, to be tested in Milton Keynes. Fulton noted that ultimately, special infrastructure may not be needed, but “there is the chance that there might be something that could enhance the reliability and operation of these vehicles” (Fulton, 2016). While this remains a grey area, the developments of the autonomous vehicle and smart network infrastructure are progressing at different rates. Continuous research on possible improvements to the road network, based on current technologies, government policies and the desires/needs of the users could possibly enhance the AI capability of these “robot-vehicles”.

It should be noted that other Autonomous Vehicle (AV) technology has already been operational in other areas of the transport industry for decades. For example, airplanes have been equipped with computer assisted flight systems to automate flying and landing from as early as 1912 and 1948 respectively (Heydarian Pashakhanlou, 2019; Charnley, 2011). In 2018 there were 64 fully automated metro lines in forty-two (42) cities, operating at a combined 1,026km. Figure 2-2 below shows how the 1,026km of operating lines are divided among the world regions. It is forecasted that by 2028 there will be over 3,800km of automated metro lines in operation, as shown in Figure 2-3 below.

In the UK, the Docklands Light Railway (DLR) which operates throughout East London, is fully automated since inception in 1987 with a Passenger Service Agent on onboard to take over, if necessary, as well as safely board and attend to passengers. This is forecasted to increase exponentially by 2020 (The UITP Observatory of Automated Metros [UITP], 2019), but the system needed for these trains is far less complex than those associated with the ConFAV, as the former runs on pre-defined tracks that are cordoned off from other vehicles and pedestrians.

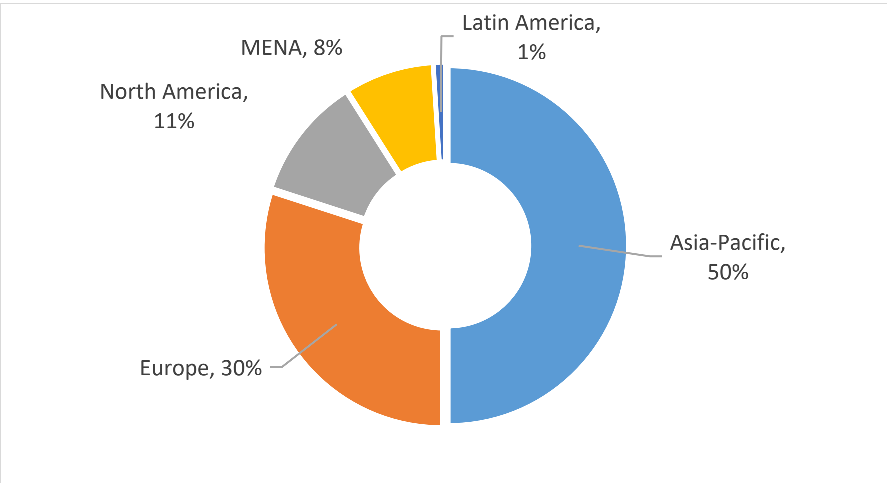


Figure 2-2 Percentage of auto lines (UITP, 2019)

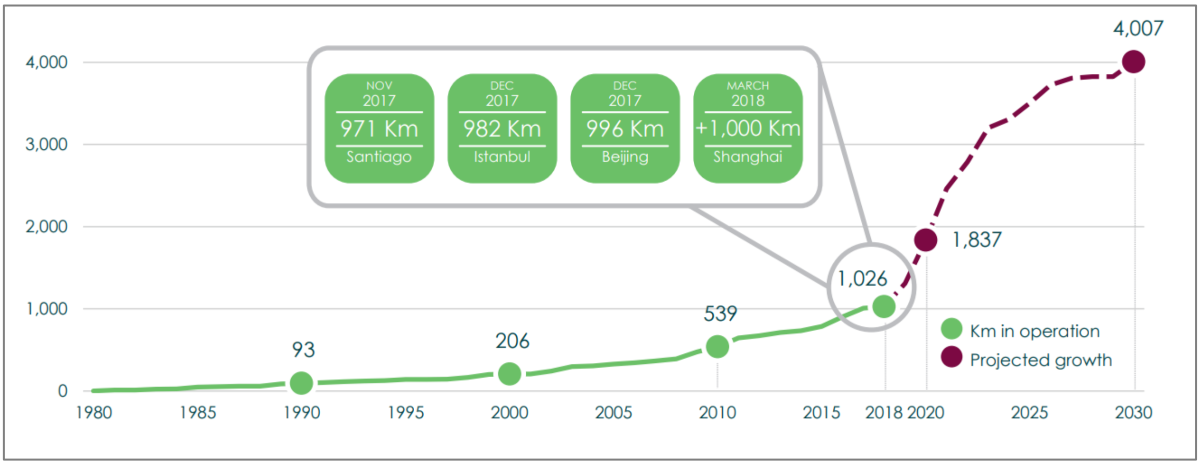


Figure 2-3 Automation growth (UITP, 2019)

2.2 The global state of the art of the connected autonomous vehicle

The past thirty years have seen major strides in the successful implementations of Intelligent Transportation Systems (ITS). Connected vehicles collect data about their surroundings and use this information to support the driver in their operation. This has been accomplished through the use of strategically placed sensors both on-board (On-board units: OBU) and along the sides of the road (Roadside units: RSU), using Vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), infrastructure-to-vehicle (I2V) and inter-infrastructure (I2I) communication technology (Guo et al., 2006). The data collection is facilitated through the use of dedicated short-range wireless communication (DSRC), which forms Vehicular Ad-hoc Networks (VANETs) that allow vehicles to exchange information about road conditions and their trajectories (Gradinescu, et al, 2007; Kishimoto et al, 2014).

Currently the connected vehicle uses radar and vision sensors to warn drivers of a range of hazards alerting them to sudden braking ahead, collision paths, deviations toward the road edge, sharp curves, slippery patches, lane closures, and risks of overturning. When hazards are detected, these systems activate mitigation mechanisms in order to counteract the problem. This is done in a variety of ways from warning messages sent to the driver to the automatic correction of vehicular operations (for example: automatic braking or lane correction) in the more autonomous vehicle.

Globally, vehicle manufacturers and large technology companies have been testing and operating driverless vehicles on public roads. So far convoys of automated trucks have already been tested under controlled conditions; AVs have been operated by the US military and most importantly, four states in the USA (California, Nevada, Michigan and Florida) have already enacted legislation permitting the controlled operation of driverless cars (Begg, 2014).

One of the most notable projects is done was by a Frankfurt-based consortium of vehicle manufacturers called the “Safe and Intelligent Mobility Testfield” (SIMTD). In this project the car-to-x (C2X) communication technology was tested in the Frankfurt-Rhine-Main area of Hesse, Germany for four years beginning 2008 (The BBC, 2013). Their C2X communication technology, encompassed both car-to-car (C2C) and car-to-infrastructure (C2I) communication. This project aimed to enhance road safety and traffic efficiency, as well as integrate value-added services, by focusing on the technical implementation and the testing of the hybrid communication system. The C2X technology allowed the exchange of anonymous information between vehicles, as well as between road users and the traffic management centres (Weiß.de, n.d.; Mercedes-Benz.com, n.d.).

Mercedes-Benz, which holds a licence to test in Nevada, also used C2X technology in a line of their vehicles, enabling the vehicles to communicate with each other via a secure cloud service (Mercedes-Benz, 2016a; Mercedes-Benz, 2016b). The company’s new E-Class is touted to boast the features shown in Figure 2-4 below.

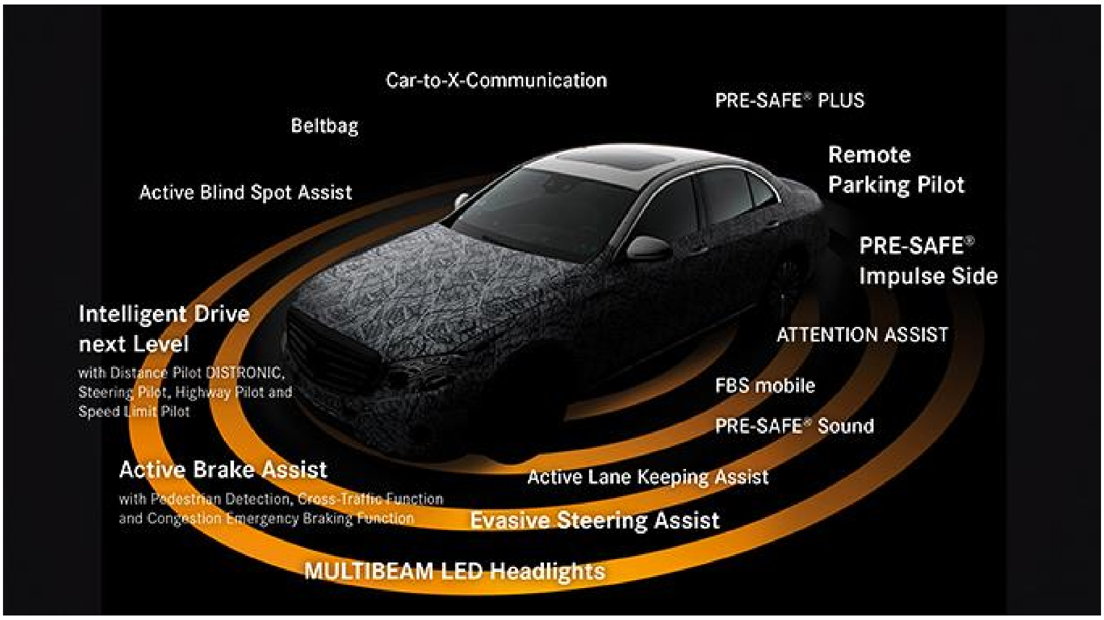


Figure 2-4 Safety features on the Mercedes-Benz E-Class (Mercedes-Benz.com, 2016)

Media reports indicate that while the USA seeks a V2V mandate, Japan has been developing its V2I technology since 2011. Since that time, Japanese researchers have promoted what is known as Universal Traffic Management Systems (UTMS), which incorporates the use of V2V, V2I/I2V and I2I communication. The practical application of this technology is constantly being researched by the UTMS Society of Japan, a body that is said to favour environmental preservation, traffic safety and congestion reduction (Kishimoto et al, 2014; UTMS.OR.JP, 2012). See appendix A for more information on their research areas.

Like many German manufacturers, Japan's automotive giant Toyota has rolled out of range of models equipped with V2V and V2I cooperative systems. According to the company's marketing information, the Lexus line features the Road Sign Assist function, that will identify and inform the driver about speed limits and road signs when travelling overseas (Traffic Technology Today.com, 2014; safecarnews.com,2015). Since 2015, Toyota has been working to develop a system that will subtly adjust a driver's actions or take over full control of a vehicle in order to prevent accidents (Knight, 2016). They have since announced plans for simulation testing of this technology near Mt Fuji in Japan. In addition to in-car technology, Toyota unveiled its first fully automated Battery-electric vehicle (BEV), pictured below in Figure 2-5, at the 2019 Tokyo Motor Show, which was specially designed to shuttle athletes at the Tokyo 2020 Olympics and Paralympics (Clifford, 2020). Toyota stated that a safety operator will be on board each vehicle, despite the vehicle being operated at SAE level 4 (as defined in Appendix B).

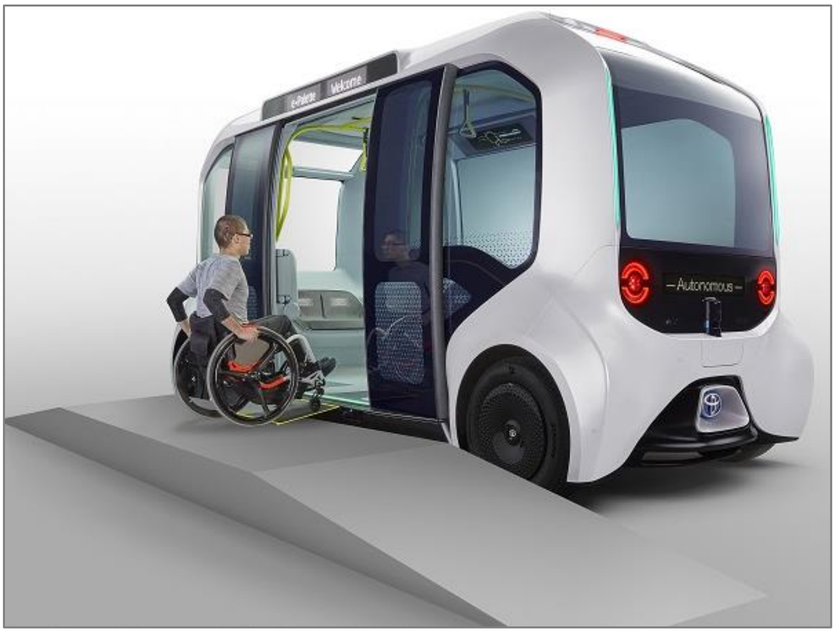


Figure 2-5 The Tokyo 2020 e-Palette (Clifford, 2020)

US/German start-up company Recogni, the developer of an AI based visual perception platform built for the autonomous vehicle (Krishnamurthi, 2021), is partnered with several top auto and tech firms like Bosch, Continental, BMW, and Toyota (Recogni, n.d.). The company's mission is to produce an AI system that allows vehicles to see farther quicker in a bid to allow more accurate decision making all while consuming minimal amounts of energy (Recogni, 2021) .

2.3 Autonomous Vehicle and Technology Trials in Europe

In the United Kingdom, an autonomous Nissan LEAF (shown in Figure 2-6 and Figure 2-7 below) was successfully introduced to the streets of Europe for the first time in February 2017, during their piloted test drive in London (Coates, A. 2017; Pitas, C., 2017; MALLEY, J., 2017; Topham, G. 2017; Williams, D., 2017). According to a January 2017 publication by Ashley Coates in The Independent, the new Nissan LEAF and Qashqai models are to be equipped with systems enabling single lane autonomous driving on motorways. The publication went on to state, that Nissan's European research and development hub in Cranfield (Coates, A. 2017).

Figure 2-6 Nissan LEAF being tested in East London (MALLEY, J., 2017)

Figure 2-7: Nissan LEAF being tested in East London (MALLEY, J., 2017)

The Nissan LEAF that was tested had four lasers and twelve cameras and was programmed to drive the route shown in Figure 2-8 below, around Beckton in east London, where it was tasked to navigate a dual carriageway and roundabouts (Topham, G. 2017). The 10km long route was chosen because it allowed the company to test the vehicle on three different types of roads (MALLEY, J., 2017).

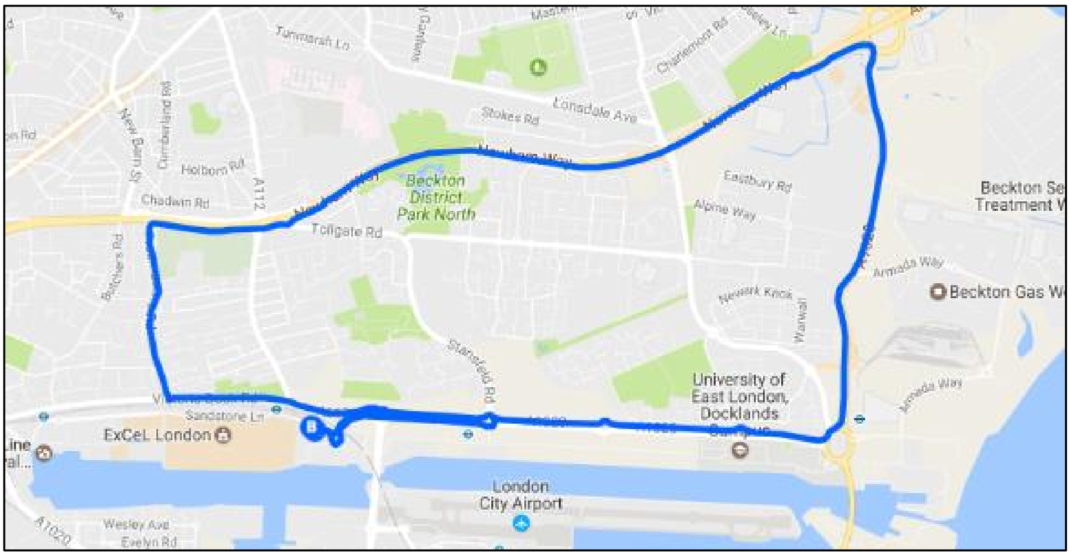


Figure 2-8: Route for London Test Drive (MALLEY, J., 2017)

During testing, the car was observed maintaining a speed of 50mph on the A13 dual carriageway, navigating around parked cars, through oncoming traffic (Figure 2-9 below), zebra crossings and in areas that lacked proper lane markings (Topham, G. 2017; MALLEY, J., 2017). The test was not entirely free from incident, however, as the pilot had to briefly take control to avoid a lorry in the neighbouring lane and a newly passed driver (displaying a "P" sign on the vehicle) ahead.

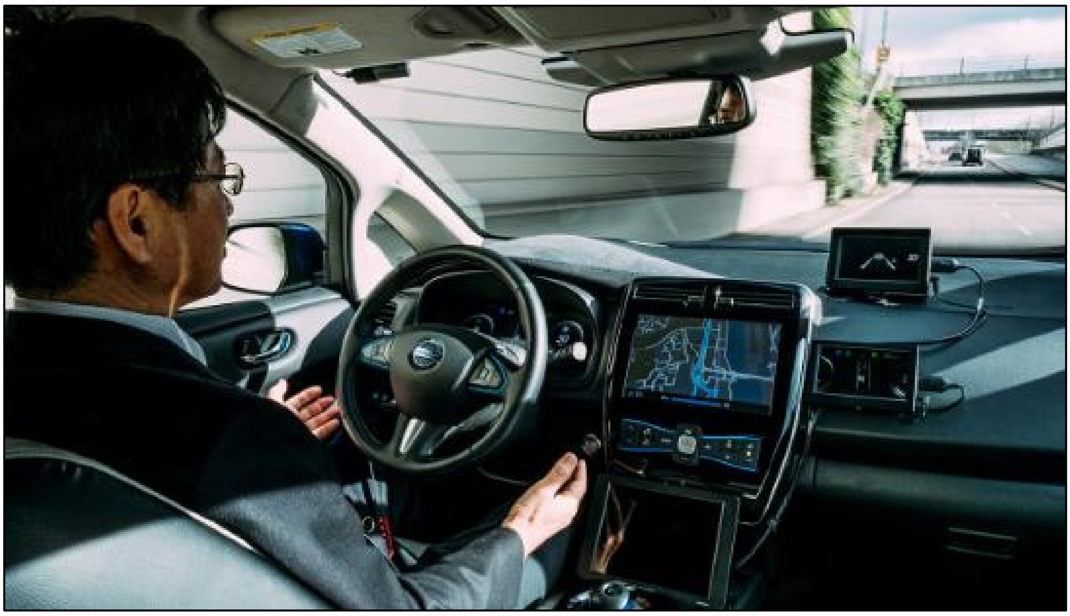


Figure 2-9: Vehicle pictured manoeuvring without interference from the operator (MALLEY, J., 2017)

Motor vehicle manufacturer Nissan has boldly declared their intention to have their experimental ProPILOT technology ready for consumers, and to have fully automated cars on the roads of Tokyo in time for the 2020 Olympics as showpiece taxis (Topham, G. 2017; Williams, D. 2017).

Humandrive, the UK government-backed project had set out to test an autonomous 100% electric Nissan LEAF equipped with GPS, radar, LIDAR (laser scanners) and camera technologies within the UK. The autonomous system was capable of making decisions to navigate roads and obstacles, to change lanes, to merge with traffic, and to come to a stop or move off at the appropriate time while traversing a roundabout or signal-controlled junction. The findings of this 230-mile autonomous journey, undertaken in November of 2019 with 2 test engineers on board, have ranked the UK as one of the best locations worldwide to develop and deploy connected autonomous vehicle technology (CCAV and Innovate UK, 2020).

The elite technology and innovation centre established and overseen by Innovate UK (Transport Systems Catapult, 2016), Transport Systems Catapult (TS Catapult), in partnership with the Mobile Robotics Group (MRG) at the Oxford University, has been leading the research into the development of self-driven pods (Oxford Mobile Robotics Group, 2016). As briefly mentioned before, the centre modelled a two-seater autonomous vehicle (as shown in Figure 2-10) which has been fitted with stereo cameras, LIDAR (light detection and ranging system) and radar-based obstacle detectors. The vehicle would continue to have a steering wheel, accelerator and brake pedal until testing is complete.

Figure 2-10: Lutz being tested by TSC and Oxford University in a public area (TS Catapult, 2016)

In an effort to contribute to shared mobility, another of TS Catapult's projects under the "Spontaneous Mobility" theme, is investigating at the use of small or medium vehicles providing on-demand services at the price of a bus, with the help of a dynamic scheduling algorithm (Begg, 2014). Results from the Milton Keynes trials will assist in the development of a fully automated booking system, that allocates vehicles and optimise route choices by using real time congestion and traffic movement data. The intention is to supplement this system with a cashless booking and billing facility called City Motion Map, which is a separate component of their programme (Begg, 2014).

According to a report in the Independent (UK) newspaper reports that the Ford Motor Company has plans to launch driverless cars in 2021, and Volvo, as part of their "Drive Me London" project, expects to introduce a fleet of driverless XC90s to London in late 2017. Volvo announce that it will have at least 100 of these vehicles on the streets of Britain by 2018. London has been targeted for the deployment of experimental driverless cars for not only Nissan, but also by GATEway (Greenwich Automated Transport Environment) a project that tests autonomous pods (as shown in Figure 2-11 below) in the pedestrianised areas surrounding the O2 in Greenwich (Coates, A. 2017).

Figure 2-11: GATEway shuttle (Coates, A. 2017)

The Swedish car company Volvo entered a joint engineering venture with Uber in 2016 to produce a self-driving system with full automation (Volvo Car Corporation, 2019). The Volvo XC90 was equipped with Uber's autonomous system, which features numerous back up system for steering, braking, and battery power, designed to bring the vehicle to a halt in the case of an emergency. Volvo Trucks also developed a connected electric autonomous vehicle called "Vera", aimed to transport goods between a logistics centre to a port terminal in Gothenburg, Sweden. This experiment (pictured below in Figure 2-12) resulted from a partnership between Volvo Trucks and the ferry and logistics company, DFDS. The joint venture aimed to design a repetitive and continuous flow operating under 40 kph (25 mph) that is responsive to demands, while maintaining maximum efficiency, flexibility and sustainability.

Figure 2-12 Vera getting ready for its first assignment (Volvo Car Corporation, 2019)

2.4 Autonomous Vehicle Behaviour

An automated vehicle's operation can be broken down by its performance of three steps (Pauca, Caruntu and Maxim, 2020):

- sensing the environment through the detection of obstacles and other vehicles;
- planning future actions using local measurements and information received through vehicle-to-vehicle communication;
- executing the planned actions while following the programmed trajectory.

As such, a majority of research focuses on the autonomous vehicle navigation and its understanding of the surrounding environment, through the use of intelligent algorithms (Duan et al., 2021; Marzbani et al., 2019; Milani et al., 2020; Valera et al., 2019; Wang et al., 2019; Zhou, Jiang and Li, 2020) as well as using the sensor data for the internal condition of the vehicle to govern the optimal driving strategy (Son, Jeong and Lee, 2020).

To enhance the overall efficiency of traffic flow, hazard detection and collision avoidance of the autonomous vehicle, it would need to be programmed to coexist in the public domain alongside human drivers, and to learn to recognise and adapt to human behaviour (Nallaperuma, De Silva, Alahakoon and Yu, 2018).

Using vehicle to vehicle communication, autonomous vehicles on similar route trajectories can travel together to increase efficiency, and this is explained in more detail below.

2.4.1 Platooning

Badnava et al in their 2021 publication defined a vehicle platoon as a group of connected automated vehicles (CAVs) traveling together at consensual speed, following the leading vehicle while maintaining a predetermined inter-vehicle distance. Platooning is said to contribute to the improvement of mobility, fuel consumption, travel time, and traffic safety (Badnava et al., 2021), and so there are many research projects funded by government bodies and private tech and/or automotive firms.

UK Heavy Goods Vehicle (HGV) Platooning project is a series of real-world trials to take place in a live commercial operating environment (HelmUK, 2019). Backed by the policy direction of the UK's Department for Transport and the technical leadership of Highways England (now known as National Highways), Transport Research Laboratory (TRL) Limited leads the consortium of project partners in achieving their research objective of understanding the requirements of operating a live platoon on UK roads.

The European Commission, under the Framework 7 programme, funded the Safe Road Trains for the Environment (SARTRE) project to study the strategies and technologies for platooning vehicles on un-modified public highways (Verdict Media Limited, 2019). The technology is meant to operate platoons on public highways, without the need for modification to the actual road infrastructure, alongside other conventional non-platooning vehicles, while addressing safety, congestion and environmental concerns. The company claims that platoons are estimated to provide up to 20% reduction in emissions, reduce collisions caused by human actions and provide smoother traffic flow increasing throughput. This project is a joint venture of 7 entities across 4 countries (Dávila and Nombela, 2011; Chan et al., 2012).

2.4.2 *Desired Speed of the Autonomous Vehicle*

The speed of the vehicle is expected to be dependent on the environment that it is driving within. However, there are other parameters that can and may affect the desired speed of the vehicle, such as coordinating with traffic signals to reduce the effects of start-stop. Audi (One of the researchers in SIMTD) has applied C2X technology called “Traffic light info online service”, which promises to give the driver the ability to maintain the speeds required to get green lights only along his/her route, and also to tell the time remaining on a red light. Researchers report that the system could reduce carbon emissions by up to 15% by reducing stop-and-go situations in the drive cycle, and cut back on congestion (Audi Deutschland, 2014).

2.4.3 *Car-Following Behaviour*

Li et al. in their 2021 publication, stated that longitudinal acceleration could be selected as an indicator of driving behaviour. They go on to explain that the main difference among drivers how they change vehicle speed, as a drivers’ perceptions of longitudinal acceleration may vary greatly. Another indicator of the driver’s characteristics was the Time Headway (THW), which describes the time it takes the front of the following vehicle to get to the rear of the leading vehicle. Thus, in their research, they used longitudinal acceleration and THW to define the driving behaviour of the autonomous vehicle (Li et al., 2021).

2.5 Lane Changing Behaviour and Congestion

Considering the route intention, desired speed and comfort, a driver may choose to change lanes, which involves the lateral movement from their current lane to an adjacent lane. Depending on the environment, this could be considered as arbitrary or mandatory lane change, where the latter must be accomplished within a given timeframe. The length of time it takes the driver from the start of the manoeuvre to the point of lane crossing, is also considered a function of the driving behaviour (Li et al., 2021).

Autonomous vehicles undertaking co-operative lane changing using coordination protocols could provide a safer and more efficient lane changing manoeuvre

(Hodgkiss, Djahel and Hadjadj-Aoul, 2019). An example of this behaviour is shown in Figure 2-13 below.

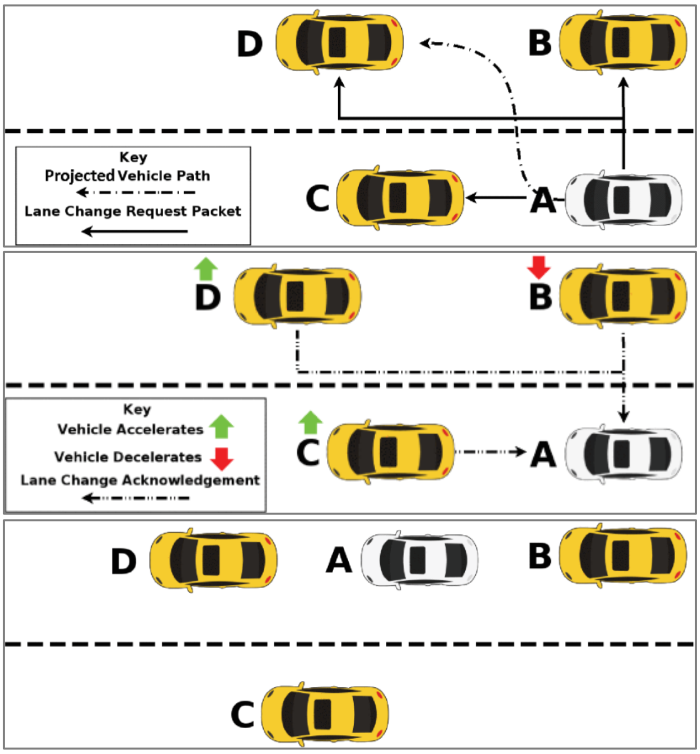


Figure 2-13 Co-operative Lane Change (Hodgkiss, Djahel and Hadjadj-Aoul, 2019)

Researchers have agreed that optimised lane-changing manoeuvres in conjunction with smaller headway gap between trailing ConFAVs have the potential to significantly reduce congestion (Domingues et al., 2018). Congestion is typically caused by the unbalanced usage of lanes and abrupt lane-changing behaviours within a high-volume traffic environment causing a chain reaction of vehicles braking and slowing down, creating what is known as a shockwave (Morino and Kage, 2021). Co-operative lane changing and platooning could be a solution to these shockwaves.

2.6 Testing Safety of ConFAVs

ConFAVs are able to acquire information about their surrounding more efficiently with high-precision sensors, potentially eliminating common human driver errors due to tiredness, maloperation, and reckless driving. Thus, they are commonly advertised as providing an efficient solution to many safety-related issues. However, fatal collisions over the years involving these autonomous technologies (Tesla, 2016; Pavia, 2018) have shown that whilst the technology is very advanced, there is still a long way to go to ensure safe driving.

Traditional road-testing method for vehicles would prove very difficult to achieve the test requirements of autonomous vehicles. Zheng et al (2020) explains that research data show that an autonomous vehicle would have to drive at least 240 million kilometres to prove that their safety parameters are not less than that of the conventional human driver. This amounts to a fleet of 100 cars being tested at 50kph continuously over a period of 6.8 years, which would need to be restarted if there were any modifications. Thus, the simulation method of testing is preferred (Zheng et al., 2020).

Time to Collision (TTC) is one of the safe driving performance matrices performance metrics for human-driven vehicles developed by the engineering community, originally developed by Hayward in 1971. There have been recent studies conducted using TTC as a surrogate safety measure with means of improving reliability, and it is not complicated to interpret (Wishart et al., 2020).

2.7 Current Gaps in Research

In a study undertaken by the National Highway Traffic Safety Administration (NHTSA) involving two light vehicles, it was determined that vehicle following behaviours were on a list of 37 pre-crash scenarios identified as the most common driving situations that lead to crash events. The operational safety of autonomous vehicles has to be quantified using defined metrics to provide a clear understanding of the level of risk associated with AV deployment on public highways (Elli et al., 2021).

In 2016 the UK government in collaboration with ATKINS released a two-stage report on the impact of connected autonomous vehicles on traffic flow, laying out the parameters that needed to be changed within Graphical User Interface (GUI) simulation software PTV VISSIM (PTV Group, n.d; PTV AG, 2019) to adequately represent their driving behaviour. They assessed nine (9) capability levels where 0 was the most cautious behaviour and 9 represented the most assertive (DfT, 2016). The European Union's Horizon 2020 project named "CoEXist", which aimed to provide vital information for the transition phase from conventional vehicles to automat-ed vehicle on urban roads, published a series of documents in 2018 which covered the technical behavioural parameter sets for Automated Vehicles (Sukennik, 2018). These behavioural sets were validated (Sukennik et al., 2018) and published for 4 types of driving logic: rail safe, cautious, normal, and all-knowing.

The shortfall of both the ATKINS and CoEXist models was that a global value was assigned to each of the Wiedemann 99 parameters, without altering the behaviour of ConFAV to act differently when following a conventional human driven vehicle, versus another ConFAV. This research project aims to bridge that gap by creating a model that differentiates between the two categories of leading vehicle (ConFAV or Conventional Human Driven), and to assess the potential impact this may have on the safety and efficiency of the road network.

3. METHODOLOGY

This research project was a quantitative study, which began with the examination of literature on the state-of-the-art systems and the matrices used in defining these advances in technology. The research objectives were achieved through different levels of research as shown in the figure below. While a comprehensive literature review was being carried out to determine the gap in research, it was found that a flexible transportation planning tool and updated transportation management models for autonomous vehicles were absent in the UK. In order to make network management suggestions or design this tool, an extensive review of the effects of autonomy on a transportation network had to be carried out. This was done using two different computer software to simulate or visualise the impact a fully autonomous vehicle (FAV) could potentially have on the road network.

The autonomous vehicle was modelled using a microsimulation software based on assumptions of possible driving behaviours. The selection of software was hinged on the need for a microsimulation tool with a Computer Aided Design (CAD) Graphical User Interface (GUI), which was also used by local councils and government regulatory offices. PTV VISSIM was selected because it was designed to assess all traffic-related aspects of a network via scientific behavioural models that simulated "realistic behaviour of all road users within the existing and planned infrastructure". The developers also issue regular updates that incorporate the latest research findings (PTV Group, 2018a). The safety analysis was carried out using a software developed by the Federal Highway Administration (FHA-USA) called Surrogate Safety Assessment Model (SSAM), because of its working link with PTV VISSIM and widely corroborated and validated outputs. The latest version (3) was used for this study.

3.1 Research Model

The model for this research can be summarised in the chart shown in Figure 3-1. The first step was to conduct a review of literature, in an attempt to understand the presence and state of the art of ConFAVs, trials undertaken and how the vehicles are meant to behave, including their safety. This was literature review was then used to determine a gap in knowledge that this research aimed to fill.

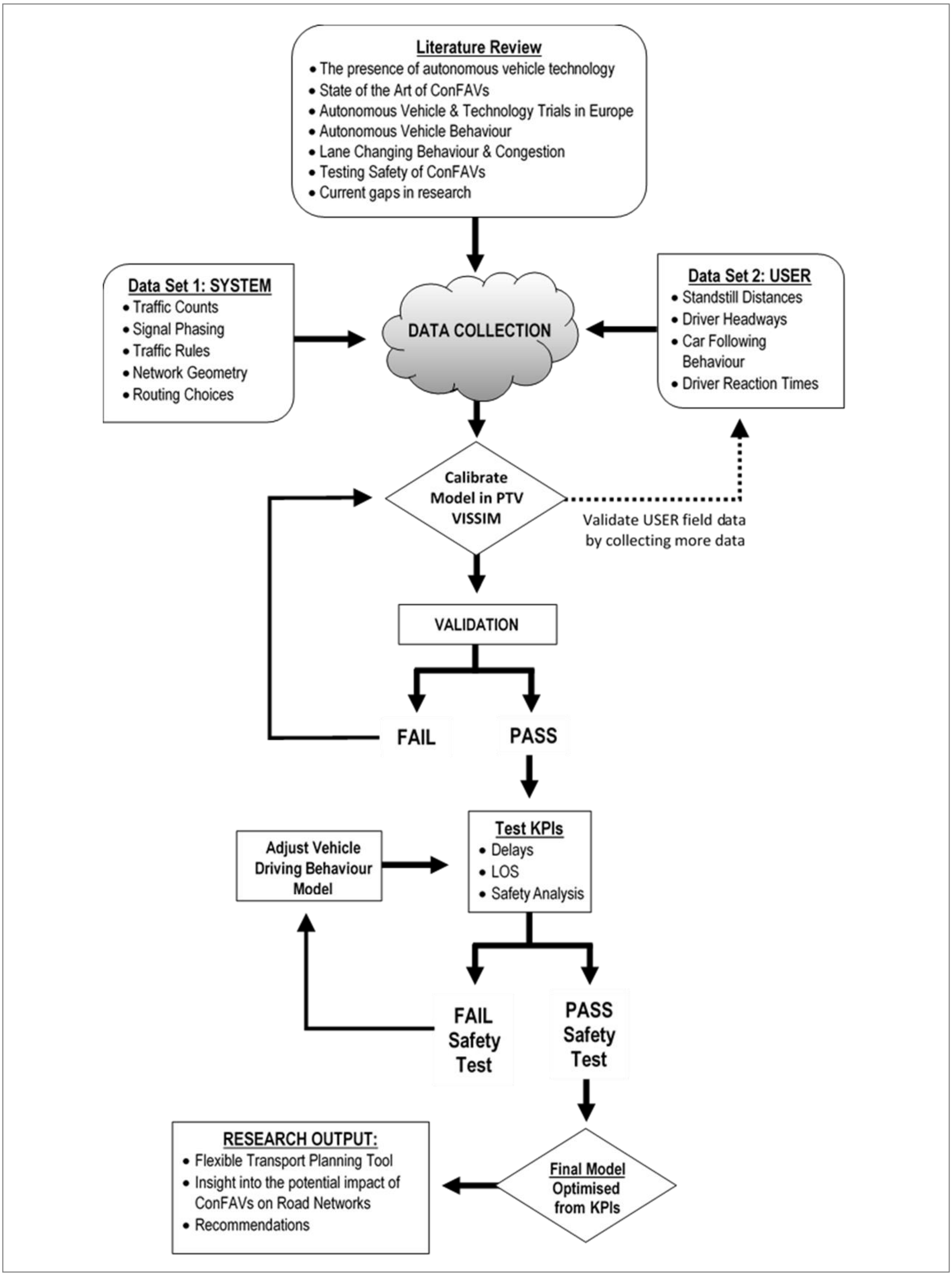


Figure 3-1: Research Model

The next step was to collect two data sets (as described in section 3.5.2 on measures of effectiveness), which were a combination of existing information and generated data derived from site observations, as well as calculations and assumptions that are corroborated by existing research. The data sets (see section 3.5.3 on Data collection) were then fed into the model to calibrate it, and once validation was achieved (see section 3.5.4 on model validation), the model was tested for its performance in average delays, levels of service (LOS) and safety (method for testing KPIs are discussed in sections 3.6 and 3.7). Once the model passed the safety analysis (see section 3.7 on Safety Evaluation), the parameters of ConFAV driving behaviour used in the successful model were retained producing the “Final Model”, which was then used as a tool capable of assessing the impact of ConFAVs on the road network for the case study in section 5. The resulting recommendations from the exercise was then listed in section 6.4 of this document.

3.2 Existing Conditions of Road Networks

The existing geometry (for example: number of lanes, length of link) and link capacity were unique to each location being tested, and the specifics discussed in detail within the microsimulation methodology sub-sections 4.2, 5.2, and 5.3.

Calculating Traffic Capacity

For the purpose of this study, the empirical approach of capacity estimation (typically used in the United Kingdom) was applied using the Design Manual for Roads and Bridges (DMRB) TA 79/99 for guidance (as shown in Table 3-1 and Table 3-2 overleaf).

Roads within each site for the case study were classified as Urban All-Purpose roads using table 1 from the DMRB TA 79/99 (shown in Table 3-1 overleaf). The capacity was then estimated for each location using table 2 from TA 79/99 (shown in Table 3-2 overleaf) dependent on whether the location being assessed was a single or dual carriageway, the width of the carriageway, and the number of lanes. Existing road classifications and capacity calculations are further detailed in sections 4.2, 5.2 and 5.3 of this report.

Table 3-1 Extracted Table 1 from TA 79/99 – Types of Urban Roads (DMRB, 1999)

Feature	**ROAD TYPE**				
	Urban Motorway	**Urban All-purpose**			
	UM	**UAP1**	**UAP2**	**UAP3**	**UAP4**
General Description	Through route with grade separated junctions, hardshoulders or hardstrips, and motorway restrictions.	High standard single/dual carriageway road carrying predominantly through traffic with limited access.	Good standard single/dual carriageway road with frontage access and more than two side roads per km.	Variable standard road carrying mixed traffic with frontage access, side roads, bus stops and at-grade pedestrian crossings.	Busy high street carrying predominantly local traffic with frontage activity including loading and unloading.
Speed Limit	60mph or less	40 to 60 mph for dual, & generally 40mph for single carriageway	Generally 40 mph	30 mph to 40 mph	30mph
Side Roads	None	0 to 2 per km	more than 2 per km	more than 2 per km	more than 2 per km
Access to roadside development	None. Grade separated for major only.	limited access	access to residential properties	frontage access	unlimited access to houses, shops & businesses
Parking and loading	none	restricted	restricted	unrestricted	unrestricted
Pedestrian crossings	grade separated	mostly grade separated	some at-grade	some at-grade	frequent at-grade
Bus stops	none	in lay-bys	at kerbside	at kerbside	at kerbside

Table 3-2 Extracted Table 2 from TA 79/99 – Capacities of Urban Roads (DMRB, 1999)

		Two-way Single Carriageway- Busiest direction flow (Assumes a 60/40 directional split)									**Dual Carriageway**			
		Total number of Lanes									Number of Lanes in each direction			
		2				2-3	3	3-4	4	4+	2		3	4
Carriageway width		6.1m	6.75m	7.3m	9.0m	10.0m	12.3m	13.5m	14.6m	18.0m	6.75m	7.3m	11.0m	14.6m
Road type	**UM**	**Not applicable**										4000	5600	7200
	UAP1	1020	1320	1590	1860	2010	2550	2800	3050	3300	3350	3600	5200	*
	UAP2	1020	1260	1470	1550	1650	1700	1900	2100	2700	2950	3200	4800	*
	UAP3	900	1110	1300	1530	1620	*	*	*	*	2300	2600	3300	*
	UAP4	750	900	1140	1320	1410	*	*	*	*	*	*	*	*

The use of average delay instead of Ratio of Flow to Capacity (RFC)

Relying on a single “acceptable” maximum value for the ratio of flow to capacity (RFC) of a road to determine its performance may give skewed results, as there may be peaks and troughs in RFC values throughout the day. The TRL article “What maximum RFC (Ratio of flow to capacity) is acceptable?” by Jim Binning, explains that an RFC value of 1.2 may not be of concern with a very low flow, whereas a value of 0.8 could become disastrous with a high flow (Binning, 2011). The article goes on to suggest that the important criteria for judging a design’s success in congestion, is to look at the average delay per vehicle on the approaches.

3.3 Assumptions and Limitations to study

PTV VISSIM 11, a microscopic traffic simulator that examines movement of individual vehicles in a network, was used to model this project, and will be referred to as VISSIM throughout the remainder of the report. The software is designed to simulate the physical movement and psychological decision-making process of each driver-vehicle unit in response to others and the infrastructure within which they operate. While VISSIM is stochastic in nature, it has no element that reports incidents of non-compliance with traffic regulations, or even safety. For this reason, a Surrogate Safety Assessment Model (SSAM) was used to identify and compare safety concerns.

The model was initially drawn based on the layout of existing infrastructure, and although there are numerous activities happening in the surrounding areas, there were some limitations due to constraints on time and resources. The original input values for network demand were calculated using the expected travel demand when the Queen Elizabeth Olympic Park is fully developed. Vehicle parameters and changes to driver behaviour were determined, based on the following assumptions, to ensure results are as close to the truth as possible:

- Driver behaviour and decision-making of the FAVs were modelled as static, as it is assumed that FAVs should all act similarly, unlike the stochastic nature of the conventional driver model.
- The model compared only cars or pedestrians to better control the experiment.

- A fixed, non-dynamic matrix for route assignment was employed, to keep the area contained to the isolated footprint, where vehicles will be tracked between named zones.
- The analysed scenarios were considered as “boundary conditions” since the FAVs were not allowed to exceed the acceleration and deceleration constraints applied.
- The suspensions of the vehicles were not taken into consideration.
- No vertical dimensions were introduced to the geometry of the network. The road surface was assumed to be completely flat.
- Power and weight distributions were not altered as these refers exclusively to vehicles categorised as HGV (PTV AG, 2018), and is therefore irrelevant to this study since the ConFAV is modelled as a motor car.
- Attributes relating to public transportation vehicles, such as location distributions for passengers boarding and alighting, as well as wait time and occupancy distributions were not included in this study.
- Trip generation, distribution and travel demand modelling were outside of the research scope, and not considered. As such, fluctuating demand from neighbouring areas/communities were not considered.
- Overtaking within the same lane was not permitted, as vehicles were made to occupy the full width of a single lane.
- To limit the potential variances in the data being analysed, the same single random seed was used for the single simulation of each scenario to ensure that the results for 0% ConFAV penetration (100% conventional vehicles in the network) were the same for all scenarios being compared.
- A Thesis licence was used for this research, and as such there are limitations in the operation of the software. These are shown in Table 3-3 below.

Table 3-3 Maximum Values for Versions

	THESIS LICENCE
Number Network Size	Default: 1
Network in km^2	10 x 10

Maximum number of signal controls	20
Maximum number of pedestrians	10,000

3.4 Defining Base Data for Simulation in PTV VISSIM

The fully autonomous vehicle (FAV) is still a concept that many manufacturers are racing to complete, therefore not a lot of data is available about modelling these vehicles. Therefore, many assumptions will have to be made when attempting to replicate the driving behaviour of the Artificial Intelligence programmed to operate the vehicle. The simulation of these autonomous vehicle dynamics could only be achieved through the manipulation of the driving behaviour parameters within the software, and if done correctly, can lead to considerable changes in the simulation results. The software allows you to make changes to the following 5 sets of parameters (PTV Vision, 2018):

- The following behaviour and car following model according to Wiedemann
- Lateral behaviour
- Lane change behaviour
- Behaviour at signal controls
- Parameters for mesoscopic simulation

In short, the FAV was modelled as a vehicle class with modified driving behaviour parameters that are based on the following assumptions (these will be explained in further detail in the forthcoming subsections of 3.3):

- Longitudinal movement according to Wiedemann 99 model
- Smaller lateral space is needed while overtaking
- Acceleration and Deceleration is done without distribution
- Desired speed is kept without any distribution
- Reaction time at traffic signals is set to zero (0)
- Speed is adjusted to arrive at green assuming C2X communication
- Smaller headways
- Vehicles of similar speed travel in platoons, keeping short and steady headways

3.4.1 Applied principles of a car following model

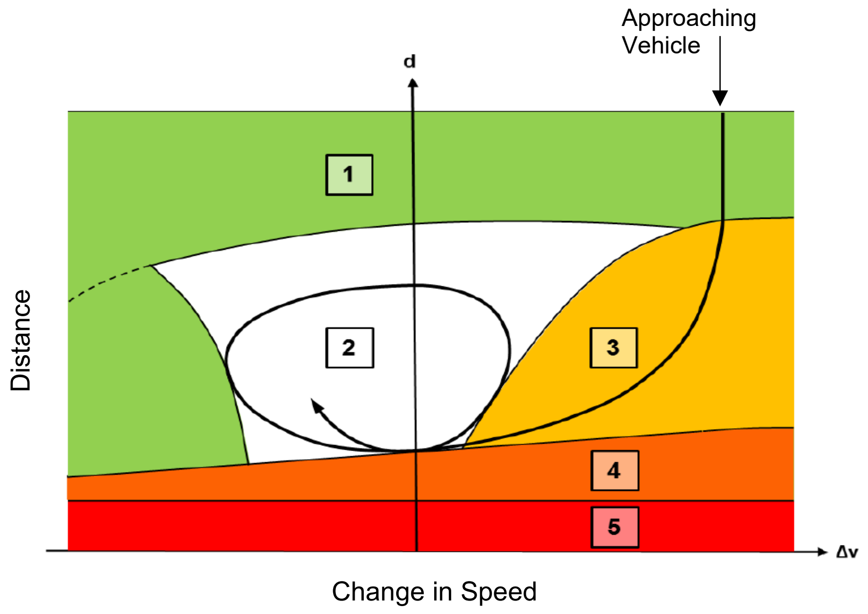
It is important to imitate the stochastic nature of traffic in simulations, to form a true representation of natural traffic flow models. The foundation of PTV VISSIM is the Wiedemann's car-following model (PTV AG, 2018). Wiedemann in his calculations used psycho-physical perception to create a stochastic distribution model. The basic concept behind his model is a driver's individual perception threshold. In this theory, a fast-moving vehicle will begin to decelerate as it approaches a slower vehicle and will do so until it gets to a speed lesser than the vehicle it follows, as it will be unable to determine the speed of the leading vehicle. Once the speed falls below that of the leading vehicle, another perception threshold is reached and the car following will slowly accelerate to match the speed of the car in front. Wiedemann based his calculations on the assumption that there are four states of driving before collision, whilst taking into consideration a distribution function of the speed and distance behaviour of the vehicle, as shown in the graph below (PTV VISSIM, 2018).

The first state the approaching vehicle will enter is the ***free flow*** or ***free driving state***, where there are no influences on the vehicle joining the procession. The vehicle will reach and maintain its desired speed. The maintenance of this speed is dependent on the physical capabilities of the individual vehicle. Older conventional vehicles without assistive driving, will oscillate around the desired speed, whereas newer human controlled vehicles with cruise control can maintain the speed.

The second state experienced will be the ***approaching state***, where the vehicle acknowledges the vehicle ahead and reduces its speed below that of the preceding vehicle.

The ***following state*** is achieved when the vehicle follows the one ahead without consciously accelerating or decelerating. The desired safety distance is maintained, but it is expected that the difference in the speeds of the two vehicles will oscillate around zero (hence the circular pattern in the graph below).

If the vehicle fails to maintain its safety distance, the ***braking state*** is next. In this state, the vehicle would have had to apply medium to high deceleration rates to bring it back to its desire safety distance, avoiding the ***collision state***.



Legend

1: "Free Flow" State
2: Following State
3: Approaching State
4: Braking State
5: Collision State

Figure 3-2: Wiedemann Car Following Model adopted by PTV VISSIM (PTV AG, 2018)

PTV then calibrated this model to ensure that changes in driving behaviour and technical capabilities of the vehicles are accounted for. VISSIM has based the calculations of acceleration during free flow traffic on the vehicle's desired speed and the assigned safety distance.

Table 3-4: Safety distances vs Driving Behaviour

Desired Safety distance	Driving behaviour
= 100%	The driver matches the speed of the vehicle ahead.
101 – 109%	The new speed is interpolated between the follower's desired speed and the speed of the leading vehicle.
≥ 110%	The vehicle will accelerate at its desired speed.

The vehicle is programmed to consider 4 vehicles ahead by default, and also vehicles in the adjacent lanes if driving in a multi-lane carriageway. If there are signal controllers in the network, then the vehicle will consider the signal from about 100 meters away before arriving at the stop line.

VISSIM is encoded to assign a driver with specific behaviour characteristics to a particular vehicle in the network, forming a driver-vehicle unit. This means that the driving behaviour is thus related to the technical capabilities of the vehicle. The software considers three categories of attributes, which directly determine the behaviour of the vehicle-driver unit:

Table 3-5: Behaviour attributes of vehicle-driver unit

CATEGORY	ATTRIBUTE
Technical specification of the vehicle	• Vehicle length
	• Maximum speed
	• Accelerating power
	• Actual vehicle position in the network
	• Actual speed and acceleration
Behaviour of driver-vehicle units	• Psycho-physical perception thresholds of the driver, e.g., ability to estimate, perception of security, willingness to take risk
	• Driver memory
	• Acceleration based on current speed and driver's desired speed
Interdependence of driver-vehicle units	• Reference to vehicles in front and trailing vehicles on own and adjacent lanes
	• Reference to currently used network segment and next node
	• Reference to next traffic signal

3.3.2 Current Assumptions for ConFAV Driving Behaviour

As discussed in section 2.7 on current gaps in research, two sets of published parameters (Atkins 2016 and CoEXist 2018) have been used to model autonomous vehicles using the Wiedemann car following rules, the assumed values of which are shown in table 3 below. A global value was assigned to each of the attributes listed, without any special conditions where the FAV followed another Connected FAV (ConFAV) or a Human Driver (HD). The simulations tested in this research made the differentiation between the two and provided different values in relation to the preceding vehicle, where normal/mid-level capabilities were adopted for the ConFAV following a human driver. The assumptions for the car following logic tested are explained in detail within the forthcoming methodology section, and the new model is called “Tested Logic” throughout the remainder of this document.

Table 3-6: Summary of Parameter Values for Wiedemann 99 Car Following Model

Wiedemann 99 Parameters	PTV VISSIM Conventional	ATKINS (2016) I	CoEXist (2018) II	Tested Logic (Present study)	
				Follow ConFAV	Follow HD III
CC0: Standstill Distance	1.5	0.5	1.0	0.5	1.5
CC1: Headway Time	0.9 ± 0.2	0.5	0.6	0.5	0.9
CC2: Following Variation	4.0	0.0	0.0	0.0	0.0
CC3: Threshold for entering ‘following’	-8.0	*default*	-6.0	-6.0	-6.0
CC4: Negative ‘following’ threshold	-0.35	0.0	-0.1	0.0	0.0
CC5: Positive ‘following’ threshold	0.35	0.0	0.1	0.0	0.0
CC6: Speed dependency of oscillation	11.44	0.0	0.0	0.0	0.0
CC7: Oscillation Acceleration	0.25	0.45	0.1	0.1	0.1
CC8: Standstill Acceleration	3.5	3.9	4.0	4.0	4.0
CC9: Acceleration at 80km/h	1.5	1.9	2.0	2.0	2.0

I. Values used for more assertive CAVs with capability level 9 on multi-lane link with merge
II. Values used for “all-knowing” FAVs – those that are fully connected
III. For CCO-CC1 when following a HD values used are for the CoEXist “normal” FAVs and capability level 5 from Atkins 2016

Currently, research around the fully autonomous vehicle is focused on, IoT and cloud services as the foundation for autonomous vehicle communication (Krasniqi and Hajrizi, 2016; West, 2016; Gerla et al., 2014), subsequent design challenges of 5G architecture (Agyapong et al., 2014; Simsek et al., 2016), Deep Neural Networks (DNNs) (Tian et al., 2018), user acceptance/experience (Rodel et al., 2014), and Interaction between the FAV and human drivers (Sadigh et al., 2018). Government-led research has grown in prominence within the UK since the establishment a new high-profile group collaborating with ministerial departments to focus on connected and autonomous vehicles (GOV.UK, 2018; Centre for Connected & Autonomous Vehicles [CCAV], 2018). Of the eighty-four projects listed in this group's 2018 publication, only one was geared towards a holistic simulation system that could potentially impact the regulatory approval processes that is required for the deployment of connected autonomous vehicles on public roads (CCAV, 2018). This is an illustration of the limited research and sparse publication of detailed modelling assumptions for FAVs even though there is a clear scope and need for considerable research around network operations and planning. Extensive knowledge about accurately modelling FAVs could address the existing need for detailed assessment of their potential over-all network impacts. Using the behavioural assumptions tabulated in the previous section, this research provides insight into the modelling of the potential driving behaviour of FAVs and their large-scale impacts on congestion, emission, and fuel consumption within a network.

Changing the Following Behaviour

A link is assigned a desired driving behaviour by changing the "Behaviour Type" attribute; driving behaviours can also be altered during the simulation. Safety distance reduction factors at the start and of a signal cannot be adjusted. When designing a vehicle class, you have the option of assigning a specific driving behaviour parameter set to a link behaviour type.

3.4.2 Modelling the Platooning of ConFAVs

While the automated driving of a ConFAV is believed to reduce the risk of accidents and improve overall safety, it is argued that their ability to form platoons could potentially increase the capacity of the highway and reduce fuel consumption. This feature maintains the desired inter-vehicle distances, a concept introduced by Adaptive Cruise Control (ACC) using radar and lidar (Vahidi and Eskandarian, 2003). Cooperative Adaptive Cruise Control (CACC) which incorporates vehicle to vehicle (V2V) communication, provides the following vehicle with more information about its preceding vehicle, and is the concept that is designed into VISSIM's platooning feature.

PTV VISSIM has created several driving behaviour attributes for the modelling of platooning among connected vehicles. The feature was meant to model the effects of platooning on overall traffic, and not to investigate the detailed trajectories of the individual vehicles within the platoon, as their trajectories are dependent on that of the leading vehicle and not their individual behaviour model. That being said, only vehicles using the same driving behaviour can form a platoon together (PTV AG, 2019a).

The platoon was modelled using the following attributes (PTV AG, 2019a; PTV AG, 2019b):

- Platooning possible (PlatoonPoss): This option within the driving behaviour must be set to true to allow platooning of vehicles that are using this driving behaviour. Only vehicles using the same driving behaviour will form a platoon.
- Max platoon approach distance (MaxPlatoonApprDist): A vehicle or a platoon of vehicles can attempt to join another vehicle/platoon from behind if its distance [m] from the last vehicle in the platoon is below this value. The default value of 250.00 m was kept.
- Maximum number of platoon vehicles (MaxNumPlatoonVeh): A platoon is capped at this number of participants. Even if another vehicle within the maximum approach distance is using the same driving behaviour it would not be allowed to join. This cap also includes any vehicles that want to leave the platoon. The study area is in an urban setting and has short link lengths, thus the platoon was programmed to operate at a maximum of 6 vehicles.
- Minimum platooning clearance (PlatoonMinClear): Minimum net distance [m] between two vehicles within a platoon, including their standstill distance. The minimum standstill distance (CC0) used in the study was 0.5m, as shown previously in Table 3-6. Thus, the PlatoonMinClear value was set at 0.5m
- Platooning follow up gap time (PlatoonFollowUpGapTm): Minimum net time gap between two vehicles within a platoon depending on the speed of the leading vehicle. This is affected by the acceleration and deceleration of the leading vehicle, and since the intention was to keep the platooning vehicles at a specific clearance, the minimum gap was set to 0.

- Maximum platooning desired speed (MaxPlatoonDesSpeed): This is the maximum speed at which all vehicles in the platoon can drive. Speed limits varied between 20mph and 30mph, so this was set at 20mph. However, the maximum platooning desired speed will not be higher than the speed of the reduced speed area.

Conflicts, lane changes and breaking the platoon

Vehicles following the lead vehicle will ***only*** react to signal head, priority rules and stop signs. The entire platoon uses the same lane and does not change lanes or drive into oncoming traffic. They will ***not*** react to other vehicles, conflict areas or reduced speed areas.

At traffic signals, or other junctions operating under a priority rule, the platoon may be split into two at the target braking vehicle that would stop at the network object.

Necessary lane changes remain active, so the vehicles within the platoon may leave the platoon according to it allocated route choice or paths of dynamic assignment, or because it belongs to a class of vehicles for which the lane is blocked further downstream (PTV AG, 2019b). The vehicle would increase the distance between itself and the preceding vehicle until a safe distance is gained for it to leave the platoon. A vehicle may change lanes only for a change of route.

If the route takes the platoon unto a new link/connector which disallows platooning or allows fewer vehicles in the platoon the platoon will split accordingly (PTV AG, 2019a).

Desired Speed and Safety distance

The maximum platooning desired speed may override that of the lead vehicle, forcing it to drive at a reduced speed. Each vehicle in the platoon will follow the lead vehicle in a coordinated manner, while maintaining a safety distance from its preceding vehicle. VISSIM calculates this distance as follows:

PlatoonMinClear + vReference * PlatoonFollowUpGapTm

Where: *PlatoonMinClear = Platooning minimum clearance*

PlatoonFollowUpGapTm = Follow-up time gap

vReference = Reference speed

The follow up gap time was kept at 0, as the intentions were to keep the vehicles within the platoon at the same distances apart. Thus, the minimum clearance was not affected by a reference speed.

Simulation Restrictions

It was not possible to use this feature to simulate platooning in the PTV VISSIM network at a vehicle input point or within a parking lot with dynamic assignment.

3.4.3 Assumptions Related to Network Parameters Adopted in the Present Study

The following assumptions were made during the alterations to the default network settings:

- A fixed, non-dynamic matrix for route assignment was employed, to keep the area contained to the isolated footprint, where vehicles will be tracked between named zones.
- Trip generation, distribution and travel demand modelling were outside of the research scope, and not considered. As such, fluctuating demand from neighbouring areas/communities were not considered.
- Attributes relating to public transportation vehicles, such as location distributions for passengers boarding and alighting, as well as wait time and occupancy distributions were not altered for this study.
- The penetration rate of the fully autonomous vehicle was modelled using the relative flow distribution table, and the model was run at 20% iterations.
- Vehicle Behaviour:
    - Gradient: Rather than using a static gradient for simulating driving behaviour, the gradient adopted was based on the z-coordinates

entered for the section of the link that the front end of the vehicle was located.

  - Traffic regulations: For the project, rules were changed to “Left-side traffic” to match that of the UK.

- Mixed Imperial and Metric Units: Parameters for lengths and acceleration were kept as default metric, while speed was changed to the imperial Miles/Hour and Feet/Minute. This was done to reflect the standard that speed limits are communicated in miles per hour within the UK.

3.4.4 Assumptions Related to Vehicle Attributes Adopted in the Present Study

Vehicle parameters and changes to driver behaviour were determined, based on the assumptions listed below:

- Vehicle suspensions were not taken into consideration.
- Only one scenario included pedestrians, and so most of the analysis was focused solely on vehicular traffic; hence no pedestrian activity was modelled in those occurrences.
- Power and weight distributions were not altered as these refers exclusively to vehicles categorised as HGV (PTV Group, 2018b), and is therefore irrelevant to this study since the ConFAV is modelled as a motor car.
- Overtaking within the same lane was not permitted, as vehicles were made to occupy the full width of a single lane.
- Autonomous vehicles are expected to accelerate and decelerate equally without distribution, until the desired speed is achieved. Therefore, ConFAVs were modelled to follow the maximum acceleration and deceleration curve of the conventional passenger car, without the upper and lower boundaries.

- Desired acceleration and desired deceleration were identical to that of the conventional passenger car, without the upper and lower boundaries.
- The average free flow speed for cars in a 20-mph zone was recorded at 26 mph in 2017 with a 86% 20 zone compliance rate (DfT, 2018), thus the desired speed for conventional cars in a 20 zone was modelled with 86% of vehicles exceeding 20mph up to a maximum desired speed of 26mph (as shown in Figure 3-3).
- The desired speed of a ConFAV is kept without any distribution as shown in Figure 3-4 below.
- Desired acceleration is increased to 110% for ConFAVs trailing another ConFAV.
- Implicit stochastics are only used with human drivers and not ConFAVs.
- ConFAVs will have a minimum lookahead distance of 0m and maximum of 300, interacting with 10 objects and 8 vehicles.
- ConFAVs will consider next turn when deciding lateral behaviours.
- ConFAV lane Change behaviour:
    - Max deceleration: own = -4 m/s^2, trail = -4 m/s^2
    - Accepted deceleration: own = -1 m/s^2, trail = -1.5 m/s^2
    - Advance merging & look ahead = ON
    - Cooperative lane change = ON (5mph, 10s)
    - Safety distance reduction factor = 0.5
    - Min headway (front/rear) = 0.5 m
    - Max deceleration for coop braking = -6 m/s^2
- ConFAV Signal Control behaviour:
    - Behaviour at amber = ONE DECISION

- Behaviour at red/amber = STOP
- Reduced safety distance = 1

- Human Driver specific changes (Validated in Section 3.4)
  - Temporary lack of attention = 1s @10%
  - Behaviour at amber = CONTINUOUS CHECK
  - Behaviour at red/amber = GO
  - Reaction time distribution = 2s ± 1s

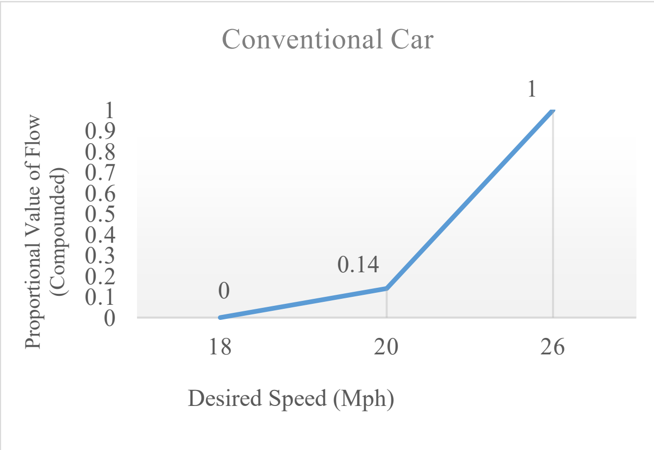


Figure 3-3: Desired Speed: Conventional Car

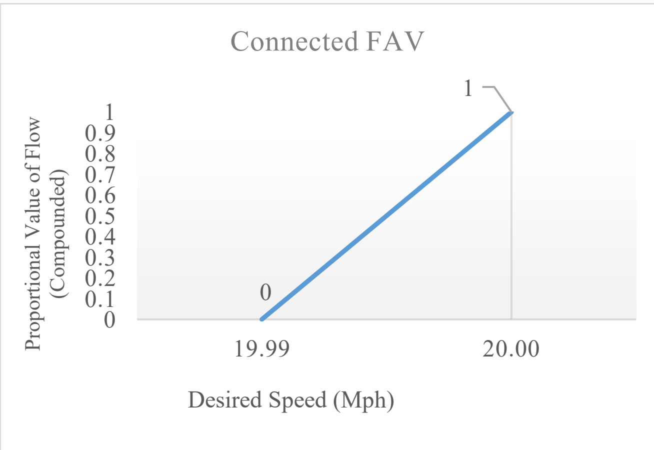


Figure 3-4: Desired Speed: ConFAV

3.4.5 Attributes to Vehicle Type

Static vehicle attributes, such as dimensions and weight were maintained as the default settings that came for the car. The other distributions were selected based on the data mentioned in the previous sections. While colour distributions are purely cosmetic and hold no influence on simulation results, a new colour was introduced for the FAV so that it can be easily identified in the graphical display.

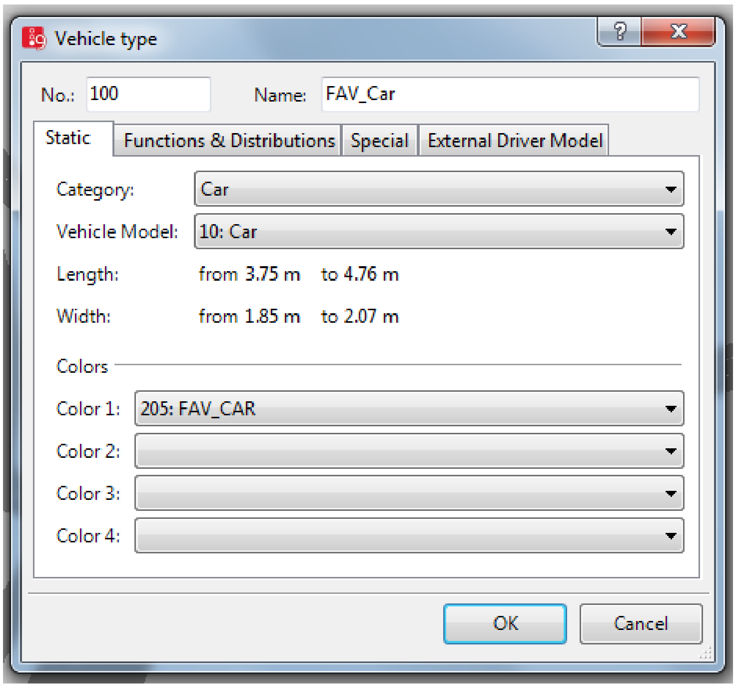


Figure 3-5: Vehicle Type: Static Parameter

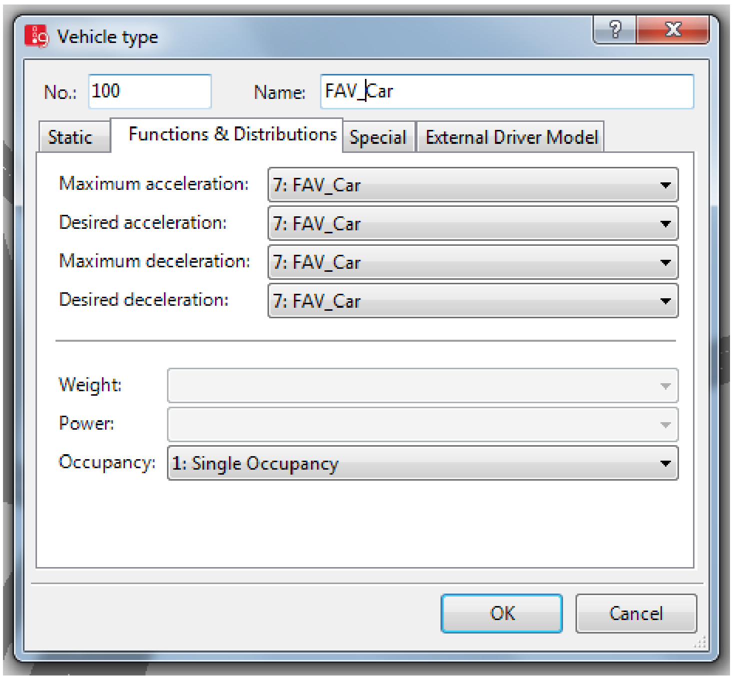


Figure 3-6: Vehicle type: Functions & Distributions

3.5 Model Calibration and Validation

The most talked about regeneration project in East is the redevelopment of the Queen Elizabeth Olympic Park (QEOP), home of the London 2012 Olympics. With 1500 new homes planned along with a cultural and educational district, the QEOP is expected to be the new urban district in East London by 2023 (London Legacy Development Corporation, 2015; London Legacy Development Corporation, 2016). The £1.75 million investment into the restoration of the QEOP waterways is expected to allow for commuters to navigate the through the community via the canals out towards the Thames (London Legacy Development Corporation, 2016). The QEOP is thus open to be retrofitted with design metrics defined for optimising the seamless introduction of the FAV on our roads. The study area highlighted in blue below (Figure 3-7) falls into 4 London Boroughs: Tower Hamlets, Newham, Waltham Forest, and Hackney. It is encased by the A12 Motorway and the trainlines serving Stratford Stations (shown in Figure 3-8 below).

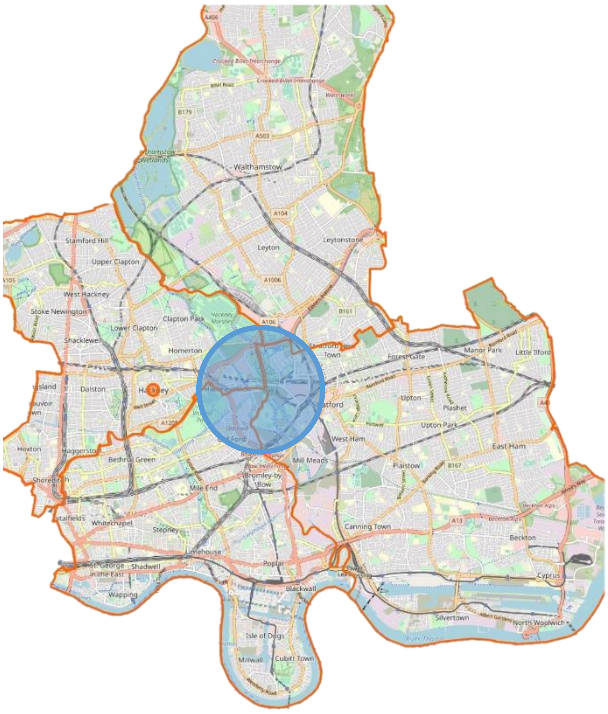


Figure 3-7: Study area falls within 4 boroughs

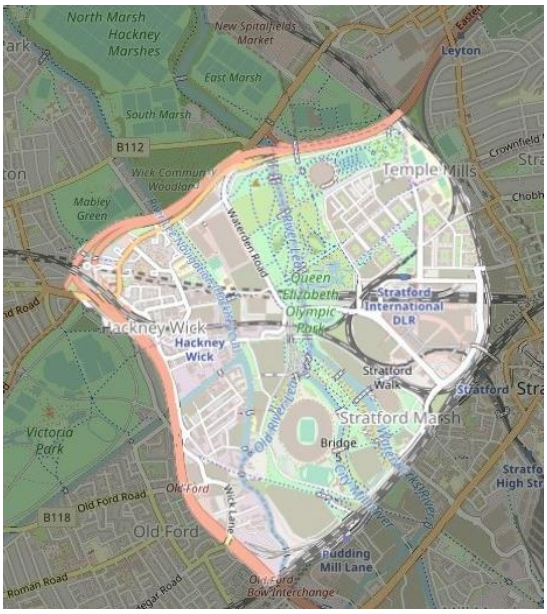


Figure 3-8: Area encased by A12 Motorway and Trainlines

3.5.1 *Microsimulation Software: PTV VISSIM*

PTV VISSIM was selected for this study because of its widespread use across the transportation industry including local consultancies and regulatory bodies within the UK, seeing more than 16,500 users worldwide. Simulations are detailed and realistic, and the COM interface allows users to interact with other applications and programme specific driving behaviours (PTV Group, n.d.). This tool allows for the alteration of numerous independent parameters that control the operation, flow, and characteristics of traffic. This software comes pre-programmed with default values for both operational and system parameters, which will be changed during model calibration. These fall under two (2) categories: System and User-defined. Some of these parameters were used to define the measures of effectiveness (MOE) for the calibration process, as explained in section 3.5.2 of this report.

3.5.2 *Measures of Effectiveness*

Measures of effectiveness (MOE) were performance measures identified as ***system-defined*** and ***user-defined*** input parameters (see Table 3-7 below).

System-defined parameters are high level and usually those that are predefined by the traffic management system (speed limits, signal timings, etc.), the geometric layout of the road network, the volume of traffic and their routing choices.

Some parameters that are user-defined in the simulation programme includes headway times, standstill distances, the driver's lack of attention and reaction time.

Table 3-7: System vs User-defined Input parameters

System-defined input parameters	User-defined input parameters
• Road geometry • Vehicle traffic counts • Signal timing • Speed limit • Routing choice	• Headway times • Standstill distances • Lack of attention • Reaction time at signals

3.5.3 <u>Data Collection</u>

Both quantitative and qualitative data were collected in the field through notetaking and video recordings. A total of twenty-four (24) recordings were made at different junctions within the QEOP to capture signal timings, speed limits, routing choices and user behaviour data. Videos were captured over a 2-hour period around Midday on a Saturday, when Westfield is known to attract a high level of patrons, and specifically on a day when there were no games at the stadium. Roads are usually obstructed to facilitate match days. The test sites are labelled in orange on the map in Figure 3-9 below.

Figure 3-9: Test sites in QEOP for data collection

All 24 recordings were used to program system-defined parameters, however, only five (5) tests sites were selected to capture the headway times, standstill distances, temporary lack of attention and reaction times of the drivers. These sites were selected due to their proximity to the A12 motorway, direct connection to the Westfield shopping centre (shown Figure 3-10 to Figure 3-19 below), and the observed traffic volumes.

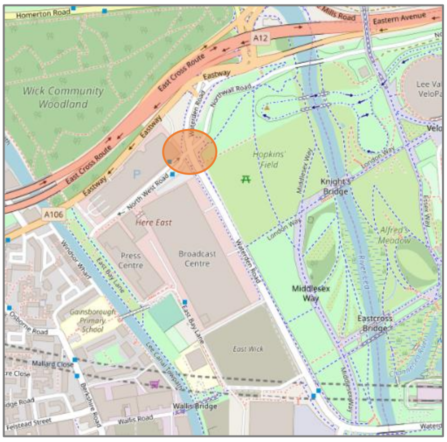


Figure 3-10: Test site “X” for data collection

Figure 3-11: Video recording of traffic at test site

Figure 3-12: Test site “I” for data collection

Figure 3-13: Video recording of traffic at test site

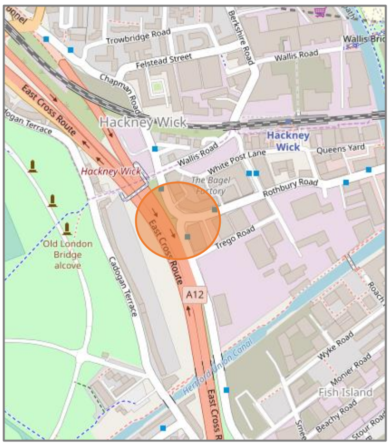


Figure 3-14: Test site “Q” for data collection

Figure 3-15: Video recording of traffic at test site

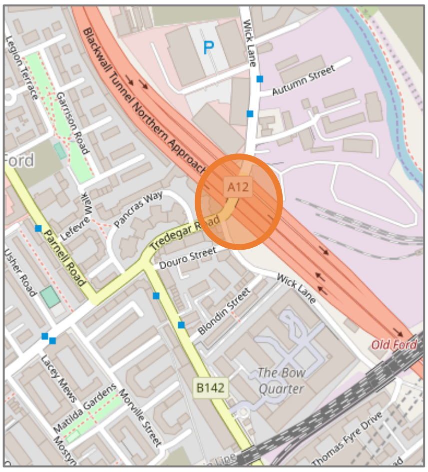


Figure 3-16: Test site "R" for data collection

Figure 3-17: Video recording of traffic at test site

Figure 3-18: Test site "U" for data collection

Figure 3-19: Video recording of traffic at test site

To aid in the calculation of distances present in the videos, HPI checks were done on each stopped vehicle to get the exact vehicle makes, so that their dimensions can be taken from their manufacturers. The software of choice was a free app on the Apple app store, from the developers HPI ltd, pictured in Figure 3-20 to Figure 3-22 below. To cross check distance estimations, Google's straight-line distance measuring tool was used on satellite imagery of the test sites on Google Maps.

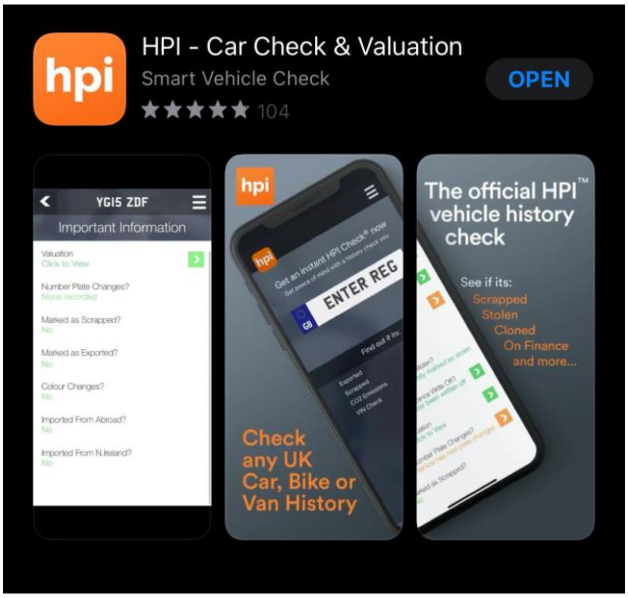


Figure 3-20: HPI Car Check & Valuation Software

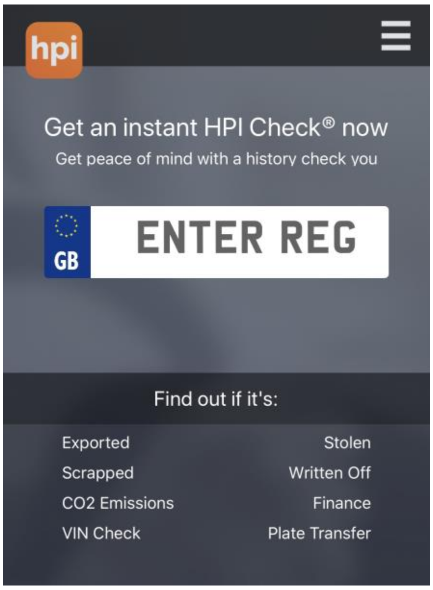


Figure 3-21: Check by registration

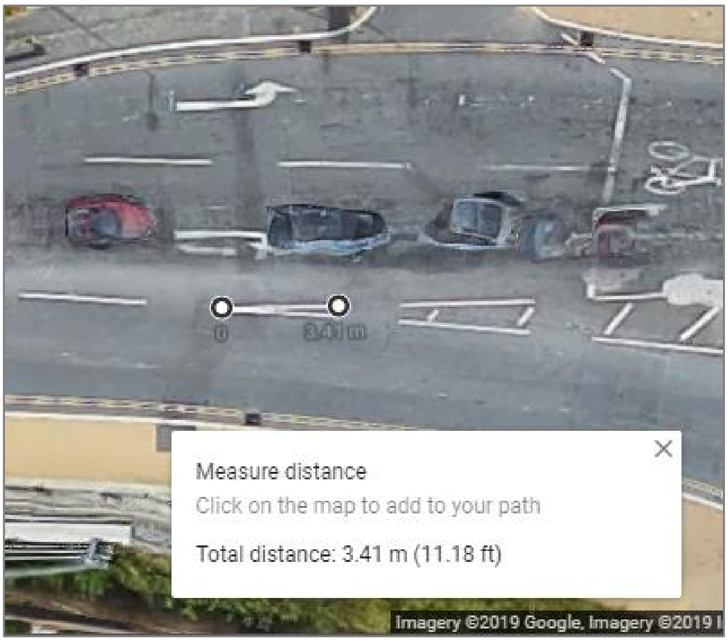


Figure 3-22: Google's straight-line distance measuring tool

After the model was calibrated with the system-defined input data, an initial run was carried out with the software's default user-defined values. Afterwards, multiple runs were conducted to verify that the new parameter (listed below) set would generate significant results.

Table 3-8: Observed parameter values

Parameter	Input Value
Standstill distances	Approx. 0.7m avg.
Headway time	0.9s ± 0.2s
Lack of attention	10% of drivers averaged approximately 1 second.
Behaviour at amber	Continuously checking
Red/Amber	Go
Reaction time distribution	Drivers averaged 2s ± 1s
Overtake in reduced speed area	Allowed

3.5.4 Model Validation

To match the field data, VISSIM was set to run for three hours with the intention of disregarding the first half hour of data as the model warms up, and the last half hour of data as the model cools down. The Department for Transport's (DfT's) Road Traffic Statistics download tool (pictured in Figure 3-23 below) was used to download raw hourly vehicle count data as well as the Annual Average Daily Flow (AADF) of vehicles that pass the count point on an average day of the year (DfT, n.d.).

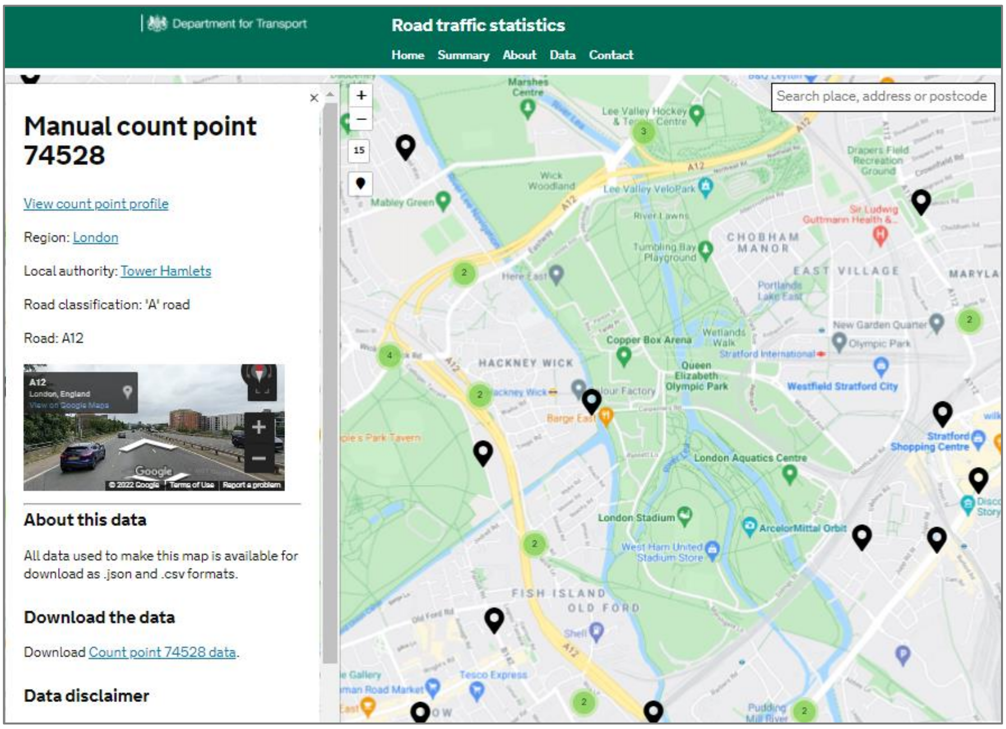


Figure 3-23: DfT's Road Traffic Statistics Download Tool

As directed by the Transport Analysis Guidance (TAG) from the UK Department for Transport (DfT), the Geoffrey E. Heaver (GEH) statistical formula was used to compare field traffic volumes with those obtained from simulation data to establish a desired reliability level and demonstrate that the base model replicates observed conditions to a sufficiently high level of accuracy. The use of the formula for validating the base model by using traffic flow comparisons is explained in the sub-section below.

Traffic Flow Comparison using GEH Statistics

Section 3.3.10 of the Transport Analysis Guidance (TAG) UNIT M3.1 Highway Assignment Modelling states that:

> *For link flow validation, the measures which should be used are:*
>
> - *the absolute and percentage differences between modelled flows and counts*
> - *the GEH statistic, which is a form of the Chi-squared statistic that incorporates both relative and absolute errors, and is defined as follows:*
>
> $$GEH = \sqrt{\frac{(M - C)^2}{(M + C)/2}}$$
>
> *where:*
>
> *M = Modelled Flow*
>
> *C = Counted (or Observed) Flow*

Figure 3-24 Extract from TAG UNIT M3.1 (DfT, 2020)

Collection of New Data Set

Data was again collected on a different day, five (5) months later. The videos were recorded on a Friday between the hours of 11am and 1pm, to capture the user-defined behaviour modelled previously. The five-months gap was to facilitate similar weather conditions, as the winter months had fallen in between the two dates.

Table 3-9: System vs User-defined Input parameters

Parameter	Data set 1	Data set 2
Standstill distances	Approx. 0.7m avg.	Approx. 0.65m avg.
Headway time	0.9s ± 0.2s	1.0s ± 0.2s
Lack of attention	10% of drivers averaged approximately 1 second.	No change
Behaviour at amber	Continuously checking	No change
Red/Amber	Go	No change
Reaction time distribution	Drivers averaged 2s ± 1s	No change
Overtake in reduced speed area	Allowed	No change

The new data set showed no change in 5 out of the 7 parameters (as seen in the table above), and minor changes in the remaining two. When simulated, these changes showed no statistically significant results, and so the final readings taken at data set two were used to calibrate the model.

3.6 Safety Evaluation

Vehicle crash statistics are traditionally used to evaluate safety within junctions, interchanges, and other traffic facilities. As collisions are quite random and infrequent, it can be a slow process to gather enough data to determine if a design or flow-control strategy needs to be improved (FHWA, 2018). This method is also incapable of assessing newly designed facilities and, in this case, new types of vehicles that would depict automated behaviours.

3.6.1 Surrogate Safety Assessment Model (SSAM) Software

Instead of using trained personnel to stand at a junction and record observed conflicts, this study conducted an automated conflict analysis through the direct processing of vehicle trajectory data using the Surrogate Safety Assessment Model (SSAM) software, which was produced by the Federal Highway Administration of the United States Department of Transportation (FHWA, 2018).

SSAM processes data describing the trajectories of vehicles driving through a traffic facility (for example, a roundabout or other type of junction) and identifying conflicts. It then calculates surrogate measures of safety that match each vehicle-to-vehicle interaction, after which it determines if the interaction meets the criteria to be considered as a conflict (Gettman et al, 2008).

SSAM analyses a single time step of a trajectory file and projects a vehicle's expected location as a function of its current speed if it were to continue along its projected path for up to the duration of the programmed time-to-collision (TTC) value.

The software offers four (4) amendable variants, as shown in Figure 3-25 below, which will determine the outcome of the analysis.

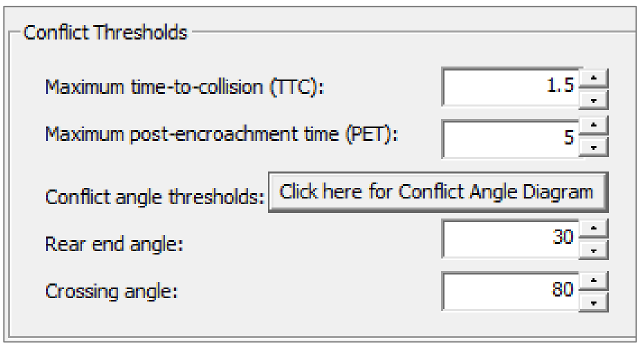


Figure 3-25: Conflict Thresholds amendable within SSAM

SSAM allows you to filter data in each trajectory file, based on the four (4) variants mentioned above, providing you with the following information (this list is by no means exhaustive):

- DR: Deceleration Rate
- GT: Gap Time
- PSD: Proportion of Stopping Distance

3.6.2 Safety Methodology

The evaluation took place as a two-stage model as shown in Figure 3-26 below. Firstly, The VISSIM simulation models were calibrated according to traffic information and driving behaviour both assumed and observed. Traffic management information were collected on site, as well as observations on average vehicle headways and traffic flow rates, then programmed into the model.

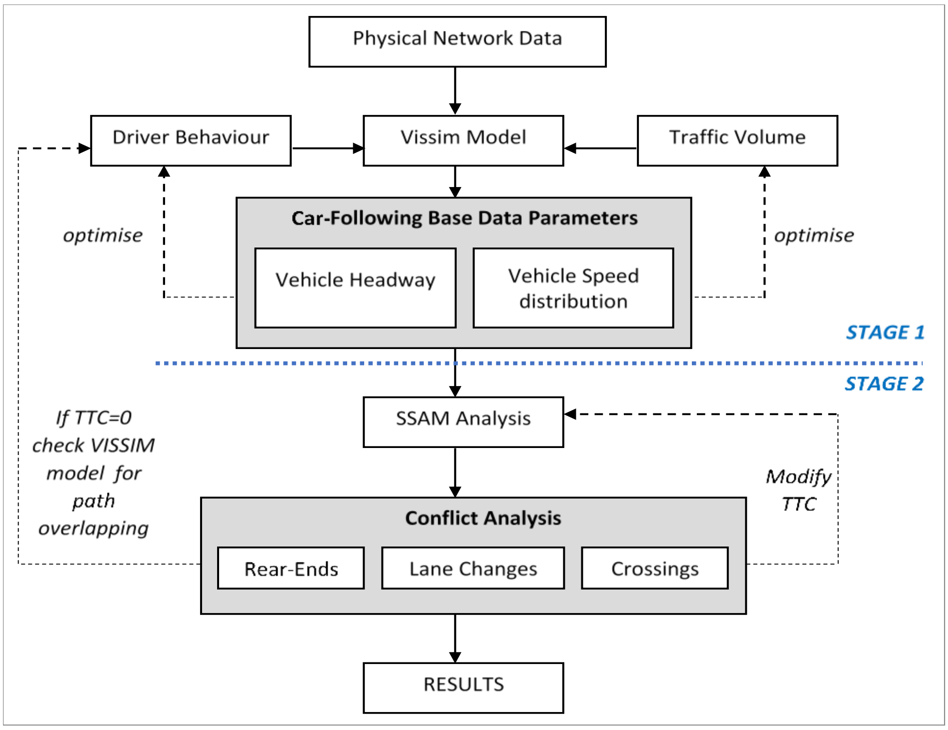


Figure 3-26: Safety Methodology

Majority of the model calibration surrounded driving behaviour parameters as described in section 3.3, where the assumptions of the autonomous vehicle were made. A sensitivity analysis was then carried out to identify which parameters had a substantial impact on the distribution of vehicular headway. The most significant parameters were that of the Wiedemann 99 car-following model, including standstill distance (CC0) and Headway time (CC1) between the vehicle and its predecessor. The fully calibrated VISSIM models were then run for 7200 seconds (2 hours) each at six (6) different autonomy penetration rates (as described in section 3.3.2), generating vehicle trajectory files readable by SSAM.

During analysis, if unrealistic Time to collision (TTC) values were recorded as zero (0), then the VISSIM model was checked for the overlapping of vehicle movement path. The links and connectors in question were then altered to eliminate any unrealistic simulated collisions.

3.6.3 *Calculating Time to Collision*

Time to collision (TTC) represents imminent danger, as this is defined as the projected time from a road user begins evasive action (e.g., braking) until they collide, if they continue along the collision course with unchanged speeds and direction (Hyd n 1987; Nadimi et al., 2016; Hawkins et al., 2018; Lu et al., 2012; Van Der Horst et al, 2019; Minderhoud et al, 2001).

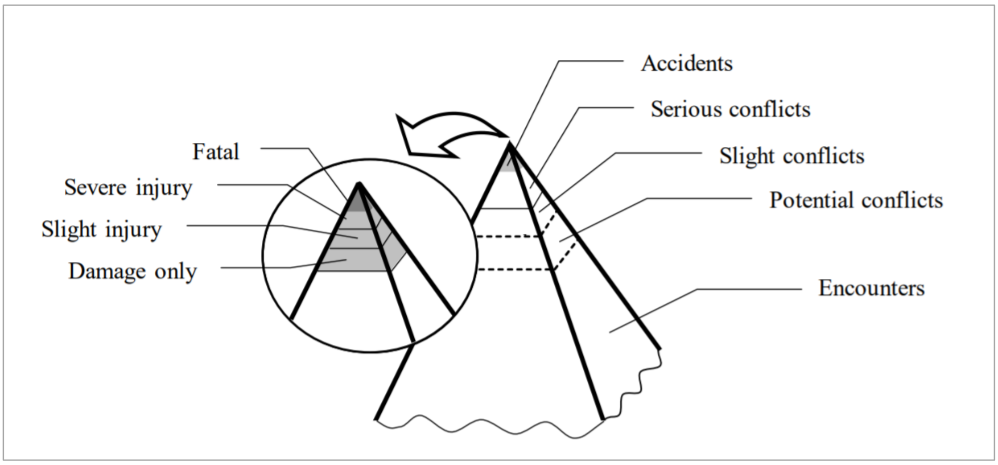


Figure 3-27: Hydén 1987 Safety Pyramid (Laureshyn et al., 2010)

When travelling along a path to collision, the time at which this path is broken determines the severity of events. As shown in n's Safety pyramid (Figure 3-27), encounters can evolve from potential conflicts into an accident, and the severity of the accident can be from damage only to fatal.

In the past, TTC was calculated by assuming that trajectories cross at right angles or are parallel as seen in Figure 3-28 below (Laureshyn et al., 2010).

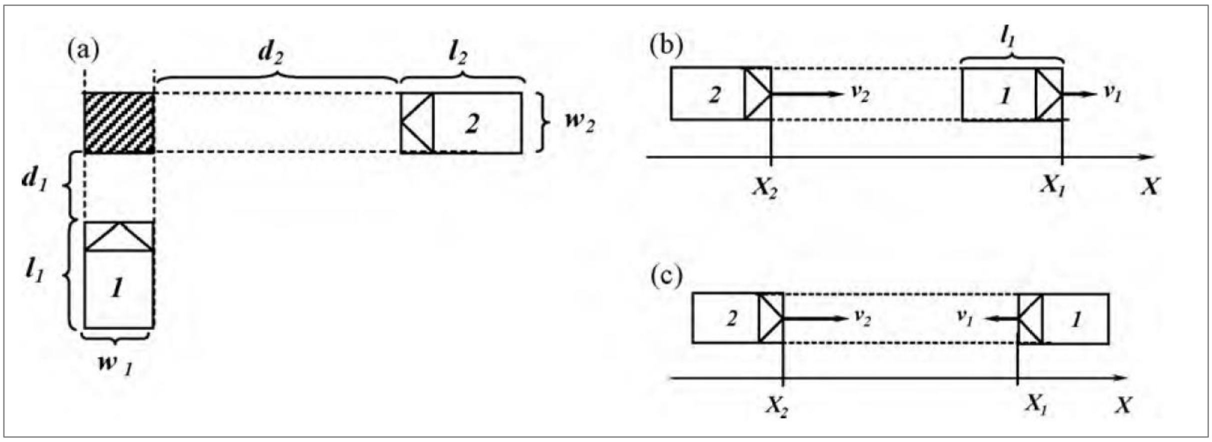


Figure 3-28: Calculating TTC for perpendicular and parallel trajectories (Laureshyn et al., 2010)

Van der Horst (1990) calculated TTC for right-angled encounters using the following equations:

$$TTC = \frac{d_2}{v_2}, \qquad \text{if} \quad \frac{d_1}{v_1} < \frac{d_2}{v_2} < \frac{d_1 + l_1 + w_2}{v_1} \tag{1}$$

$$TTC = \frac{d_1}{v_1}, \qquad \text{if} \quad \frac{d_2}{v_2} < \frac{d_1}{v_1} < \frac{d_2 + l_2 + w_1}{v_2} \tag{2}$$

Where:

- d_1 and d_2 are distances from the fronts of vehicles 1 and 2 respectively (as illustrated in Figure 3-28a)
- l_1, l_2 and w_1, w_2 are the lengths and widths of vehicles 1 and 2, respectively.
- v_1 and v_2 are the speeds of vehicles 1 and 2, respectively

Minderhoud and Bovy (2001) calculated parallel encounters as follows:

Rear-end collisions (Figure 3-28b):

$$TTC = \frac{X_1 - X_2 - l_1}{v_1 - v_2}, \quad \text{if} \quad v_2 > v_1 \tag{3}$$

Head-on collisions (Figure 3-28c):

$$TTC = \frac{X_1 - X_2}{v_1 + v_2} \tag{4}$$

Where:

- X_1 and X_2 are positions of vehicles 1 and 2 respectively

In reality there are many other angles of approach other than right angles and parallel collisions, and within each angle there are many types of collisions that can take place (as seen in Figure 3-29).

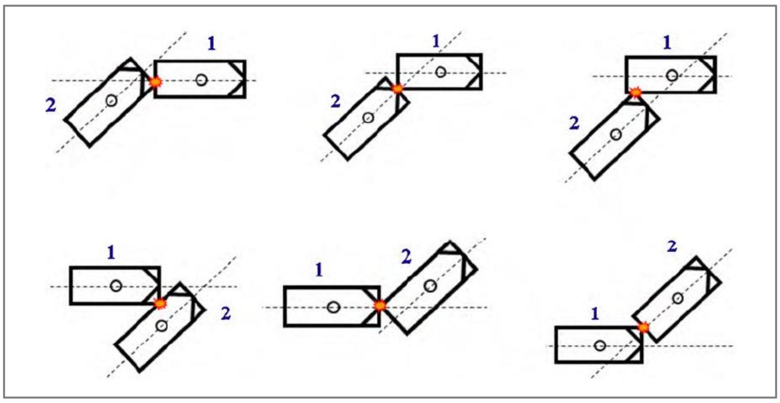


Figure 3-29: collision types at the same approach angle (Laureshyn et al., 2010)

TTC is a continuous parameter and could be calculated for any moment if road users continue along a collision course (Laureshyn et al, 2010), and if two vehicles approach each other at an angle, there are many types of collisions possible for the same angle. Figure 3-29 shows an example of collision types assuming the vehicles both have a rectangular form.

As it would be impractical to calculate the TTC for all possible collision types at each angle for each vehicle type, the “Conflicting Speed vs Time-to-Accident” chart (Figure 3-30) was used to derive a value.

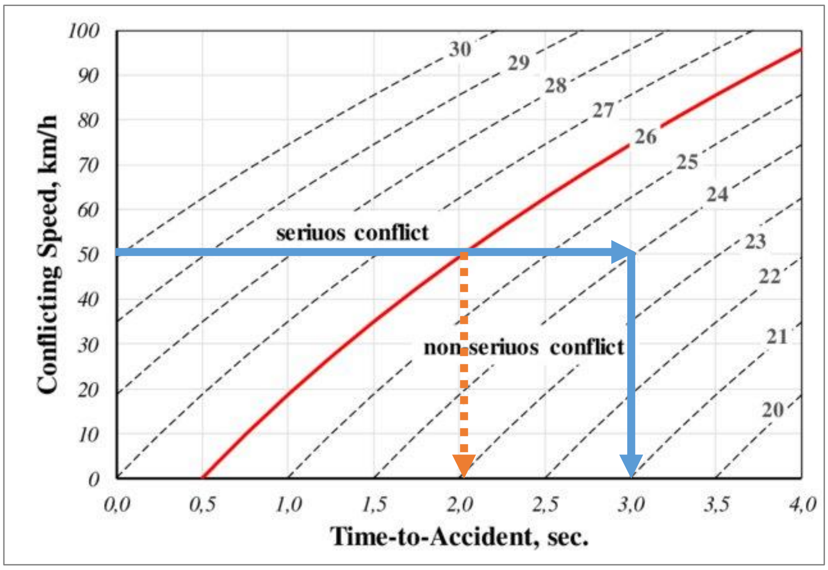


Figure 3-30: Conflict Speed VS TTA (Srie Kusumastutie and Rusmandani, 2019)

The network links had speed limits that varied between 20mph and 30mph (approximately 48.28kph). Using the Time to Accident vs Conflicting speed graph in Figure 3-30 (Srie Kusumastutie and Rusmandani, 2019), at 50mph and severity level 24, a Time to Accident maximum of 3.0 was selected to be used in the SSAM evaluation therefore increasing the sample size to include some non-serious conflicts. The nonserious conflicts were later filtered out of the sample by assessing up to severity level 26 (TTC = 2.0), for a comparison of the two data sets.

3.6.4 Calculating Post Encroachment Time

Post encroachment time (PET) represents potential danger and is calculated as the time that elapses between the departure of one vehicle and the arrival of a trailing vehicle in the exact same location (Hyd n 1987; Nadimi et al., 2016). Both TTC and PET are used to determine the seriousness of collisions, as the smaller the minimum values the higher the probability of collision.

To have a clear understanding of the difference between TTC and PET, Figure 3-31 below illustrates the timeline for a point of conflict (Gettman and Head 2003). The trajectory of the crossing vehicle is depicted by the top curve, and the through vehicle is the bottom curve. After the vehicle crosses time step 1 (t1), the crossing vehicle enters the encroachment area to begin its turn left. At t2 the approaching through vehicle acknowledges that the possibility of a collision and begins to apply its breaks. Once the rear bumper of that vehicle leaves the encroachment point at t3, the TTC and PET countdown will begin. If the through vehicle carries on without braking, the projected time it took to arrive at the conflict point (t4) would determine the TTC. The actual arrival time at the point of conflict (t5) will determine the PET.

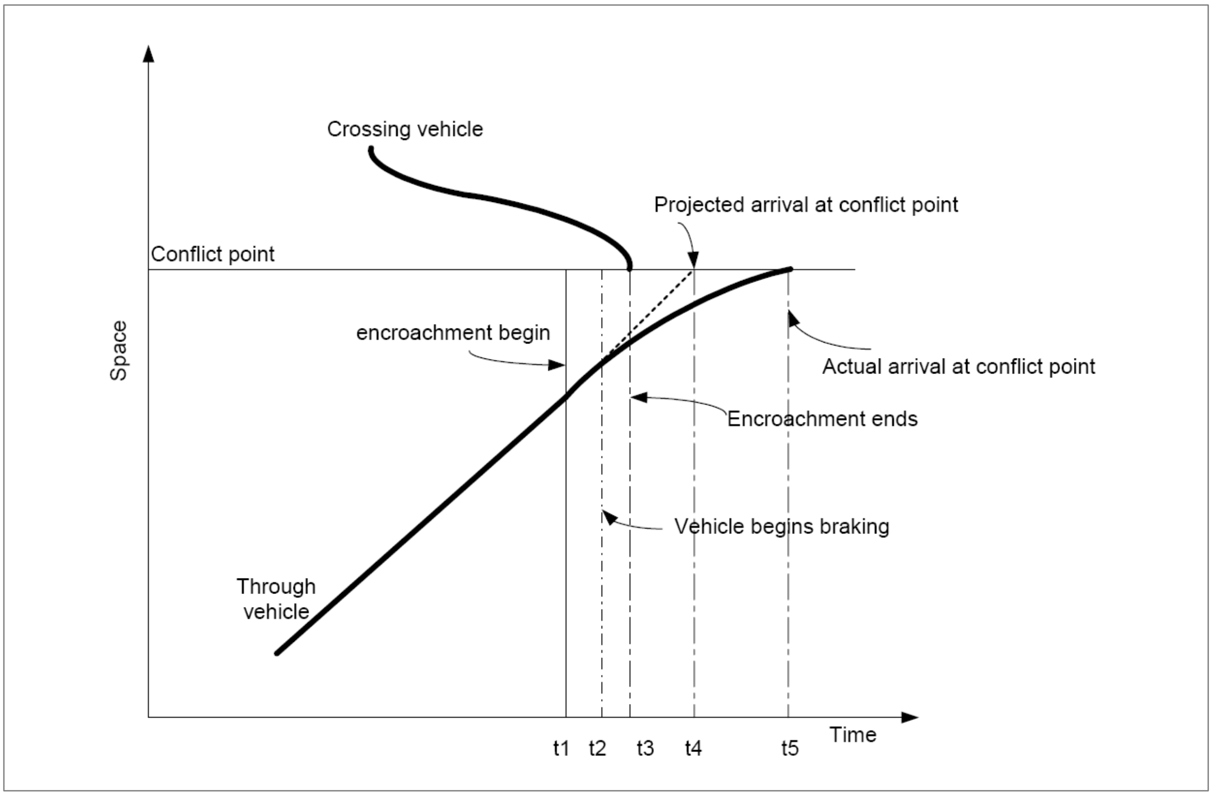


Figure 3-31: Conflict Point Diagram (Gettman and Head, 2003)

The PET value was calculated based on the critical time gap (t_c) for a minor-street vehicle to move off and join a major-street traffic stream. This research has implemented the values from the Highway Capacity Manual (2000) for the base critical gaps ($t_{c,base}$) of vehicle movements within a two-way signal-controlled (TWSC) junction, shown in Table 3-10 below.

Table 3-10: Base critical time gaps for TWSC Junctions (TRB, 2000)

Vehicle Movement	Base Critical Gap, $t_{c,base}$ (seconds)	
	Two-Lane Major Street	Four-Lane Major Street
Left turn from major	4.1	4.1
Right turn from minor	6.2	6.9
Through traffic from minor	6.5	6.5
Left turn from minor	7.1	7.5

For this safety analysis, it was assumed that the maximum accepted time a vehicle would take to safely join a traffic stream without becoming a hazard to the succeeding vehicle ($t_{c,base}$), could be used as the maximum PET before the trailing vehicle develops the potential of a serious conflict. As this study examined a mix of two and four lane major road, the highest $t_{c,base}$ value of 7.5 was implemented.

Calculating Conflict Angles

The angle of conflict is calculated based on the angle at which the vehicles will meet at a hypothetical collision point (US department of Transportation, 2008). Small acute angles mean that the vehicles were almost on the same trajectory, and larger angles suggest that the vehicles were on a head-on course. Positive angles suggest the second vehicle is approaching from the right and negative means approaching from the left. In most cases, the angle of conflict determines the conflict classification, but link and lane information may change the rules altogether. If both vehicles are on the same link and lane, then regardless of the angle, the conflict will be classified as a rear end. This analysis used the following classification also shown in Figure 3-32 below (US department of Transportation, 2008).

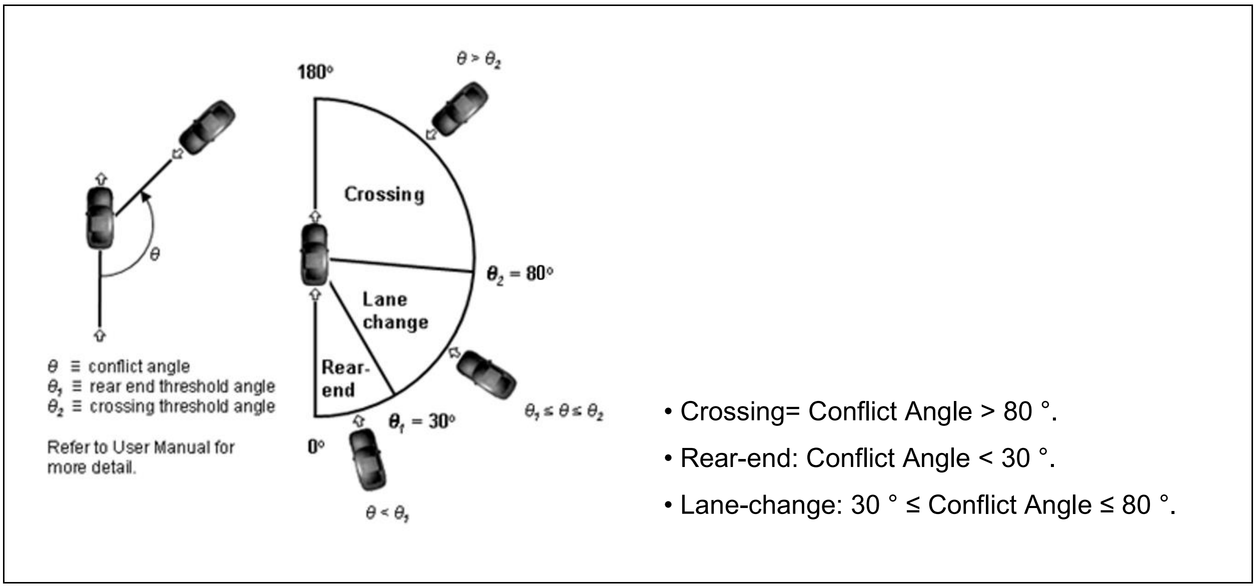


Figure 3-32: Angles of conflict explained (US department of Transportation, 2008)

Thresholds for SSAM Analysis

Based on the above calculations and assumptions, the conflict thresholds for analysis were concluded as shown in Table 3-11 below.

Table 3-11: Conflict Thresholds used for analysis

Maximum Time-to-Collision (TCC)	3.0 s then 2.0 s
Maximum Post Encroachment Time (PET)	7.5 s
Rear-End Angle	30 °
Crossing Angle	80 °

Severity of Conflict

The severity of traffic conflicts was calculated by the sum of two scores:

- Time to Collision (TTC) and
- Risk of Conflict (ROC).

The ROC is a subjective measure of the seriousness of conflicts (Sayed and Zein, 1999), and is independent of the TTC score, even though a high TTC score could typically means an equally high ROC score. The sum of the TTC and ROC gives the overall severity score, which ranges from 2 to 6, with 6 being the highest risk or more severe conflicts. The TTC and ROC scoring bands are detailed in the table below.

Table 3-12 TTC and ROC Scores (Sayed and Zein, 1999)

TTC and ROC Scores	Time to Collision (TTC) in seconds	Risk of Collision (ROC)
1 (potential)	1.6-2.0	Low Risk
2 (slight)	1.0-1.5	Moderate Risk
3 (serious)	0.0-0.9	High Risk

3.7 Efficiency Evaluation

Efficiency of the network was evaluated using travel time, by assessing vehicle delay and level of service of the network (as shown below).

Travel Time Tests:

a. *Vehicle Delay*
b. *Level of Service (LOS)*

3.7.1 Vehicle Delay

As discussed in section 3.2, delay was the preferred method of evaluation, as a single value RFC value cannot account for peaks and troughs in traffic flow. The software calculates the delay of a vehicle on its route choice by subtracting from its actual travel time a theoretical one in which there were no other vehicles, and/or no signal controls or other reasons for stops to occur (PTV Group, 2018), and does not consider deceleration in reduced speed areas.

In this stage of the research, there were no public passenger vehicles dropping off passengers, or allocated parking, so the delay due to braking before a PT stop and/or subsequent acceleration after a PT stop was not a factor in the calculation of the delay. If no vehicle is captured in the time interval, then this is left blank as there is nothing to compare it to. This information from the routes in question would then be used to populate Table 3-13 below.

Table 3-13 Test run in a signal-controlled junction

Movement \Direction	Average Queue Length*	Max Queue Length	Vehicles (ALL)	Level of Service (ALL)	Vehicle Delay (ALL)	Stop Delay (ALL)	Stops (ALL)
SW-E	2.335	6.885	1	LOS_D	45.940573	41.13758	1
E-SW	29.068	63.749	1	LOS_A	1.514332	0	0
NW-E	5.495	26.205	7	LOS_A	6.248609	3.055862	0.571429
NW-SW	5.495	26.205	5	LOS_B	14.828725	10.901376	0.6

** Note: The average queue length (maximum distance between the traffic counter and the vehicle) is calculated by measuring the current queue length in each time step, then calculating the arithmetic mean per time interval.*

3.7.2 Level of Service

The research used the recorded delays to determine the subsequent level of service (LOS) on that link/route, which was calculated differently if the junction is signal-controlled or not (shown in Table 3-14 below). The LOS parameters within the software were programmed according to the American Capacity Manual of 2010 (PTV Group, 2018), and no changes were made to this attribute*.

** Note: As the **ratio of flow to capacity** is used in the UK, a comparison of methods has been discussed in more detail in section 5.4.1 on the congestion performance for Site A, and 5.5.1 on the congestion performance for Site B.*

Table 3-14: LOS calculation parameters adapted from PTV VISSIM 10 Manual 2018

LOS	Time Lost in Seconds	
	Signal Controlled	Not Signal Controlled
A	Loss time < 10 seconds or no volume	
B	>10s to 20s	>10s to 15s
C	>20s to 35s	>15s to 25s
D	>35s to 55s	>25s to 35s
E	>55s to 80s	>35s to 50s
F	>80s	>50s

4. MODELLING DRIVING BEHAVIOUR OF THE CONNECTED FAV

4.1 Introduction and Outline

Research is being carried out worldwide on the Connected Fully Autonomous Vehicle (ConFAV) both on private and on public roads, as they drive autonomously to a pre-set location with the aid of sensors and data connections. However, there is little published information on the assumptions and actual values of parameters underpinning the driving behaviour of the vehicles. This research identifies two published behaviour models and creates a third, which takes into consideration varying driving behaviours of the ConFAV dependent on whether it is following another of its kind versus a conventional human driver with no data connectivity (outlined in section 3.3.2). PTV VISSIM traffic microsimulation software was used for the simulation trials, and SSAM3 for safety analysis.

Most of the research papers reviewed looked specifically at ConFAV performance in junctions, so three types of junctions were modelled to observe changes over different penetration rates. In the simulations, ConFAVs were added into the network at 20% intervals and the delays, emissions, and fuel consumption were recorded, and the performance of each behaviour model compared. The safety of said models were later analysed by determining the number, types, and severity of conflicts within each scenario. The assumptions for base data remain the same as outlined in section 3.3. Three common types of junctions in the UK were selected for this part of the research, and the capacities of each discussed in section 4.2 below:

- Roundabout with 3 arms.
- Priority junction – a minor road joining a Major Road
- Signal controlled 3-way junction

Test runs were made at iterations of 20% penetration rates to observe the impact the FAVs had on each scenario. See section 4.3 for simulation results explained.

This chapter will be broken down as follows:

1. Chapter Introduction and Outline
2. Microsimulation Methodology
3. Findings & Analysis
4. Conclusions & Recommendations
5. Chapter Summary

4.2 Microsimulation Methodology

Whilst the design of the junctions was done specific to UK standards, the findings can be applied to any international framework. The chosen method of software simulation was different for each type of junction. In each junction, the manipulation of the base data remains the same, but the treatment of conflict areas was entirely different. This will be explained in detail throughout in the sub-sections to follow.

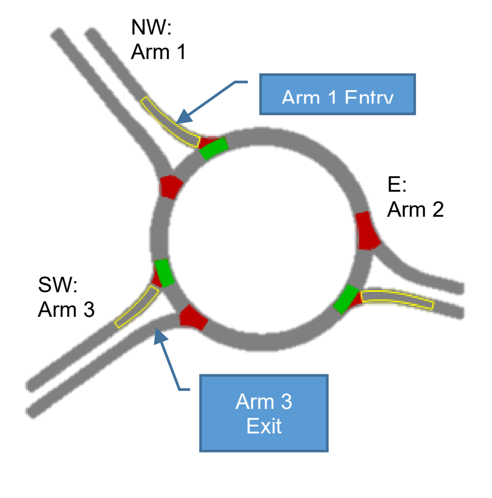
4.2.1 Simulating the Roundabout

In this experiment, the Southwest arm (SW: Arm 3) was a minor link (TA 79/99 class UAP4) that joined with a major road (TA 79/99 class UAP3) running from Northwest (NW: Arm 1) to east (E: Arm 2). The junction type considered was a roundabout. The junction is in a built up area, so the speed limit applied to all roads were 20 miles per hour (mph).

Vehicle Input and Route Decisions:

The model was run with the following traffic volume per link, capacity (calculated using TA 79/99), and the route decisions shown in Table 4-1 below.

Table 4-1: Roundabout Route Decisions



ARM	Veh Input Volume	Flow to Capacity Ratio	Route Decision
1: NW Major Link	600 Vehs/hr	0.46	SW : E : u-Turn 70% : 25% : 5%
2: E Major Link	600 Vehs/hr	0.46	SW : NW : u-Turn 25% : 70% : 5%
3: SW Minor Link	150 Vehs/hr	0.13	E : NW : u-Turn 45% : 45% : 10%

Vehicle Composition and Relative Flows:

The model was run at 20% iterations. The penetration rate of the fully autonomous vehicle was modelled using the relative flow distribution table shown below.

Table 4-2: Vehicle composition and relative flow distribution table

FAV %	Vehicle Type	Desire Speed Distribution	Relative Flow
0% FAV Penetration	Car	Car 20 mph zone	1.000
	ConFAV	FAV 20 zone	0.000
20% FAV Penetration	Car	Car 20 mph zone	0.800
	ConFAV	FAV 20 zone	0.200
40% FAV Penetration	Car	Car 20 mph zone	0.600
	ConFAV	FAV 20 zone	0.400
60% FAV Penetration	Car	Car 20 mph zone	0.400
	ConFAV	FAV 20 zone	0.600
80% FAV Penetration	Car	Car 20 mph zone	0.200
	ConFAV	FAV 20 zone	0.800
100% FAV Penetration	Car	Car 20 mph zone	0.000
	ConFAV	FAV 20 zone	1.000

Desired Speed Distribution:

The speed distribution is considered to be of major importance, as this has a direct connection to link capacity and average travel times. It is programmed within the software that is there are no hindrances such as signal controls or other road users, the driver will travel at its desired speed. The area in consideration is assumed to be built up and as such the speed on the link is limited to 20 mph. As this is junction is assumed to be in a built-up area, a 20mph speed limit is applied to the link. As mentioned previously in section 3.3.3 above, the desired speed distribution of the conventional car and connected FAV used in this case study are shown below. Approaching the roundabout, a reduced speed zone of 10 mph is applied, as drivers slow down to prepare to give way.

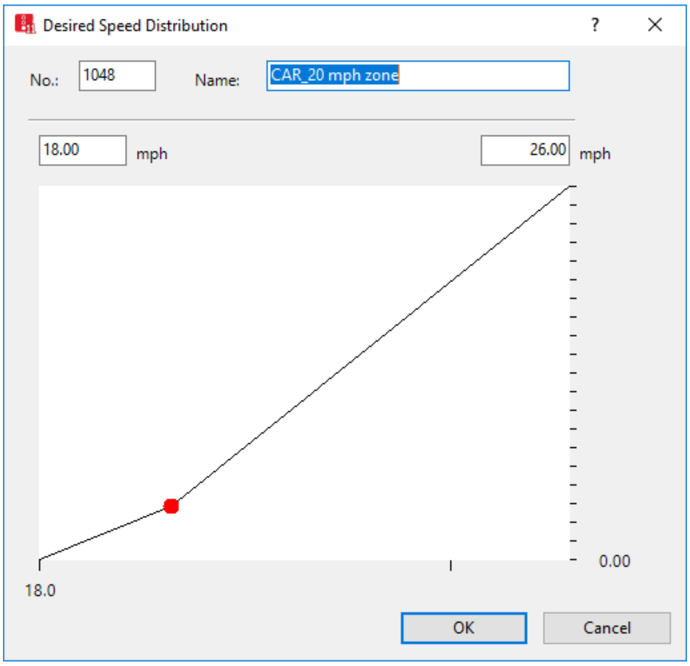


Figure 4-1 Desired speed Distribution for conventional cars in 20mph zones

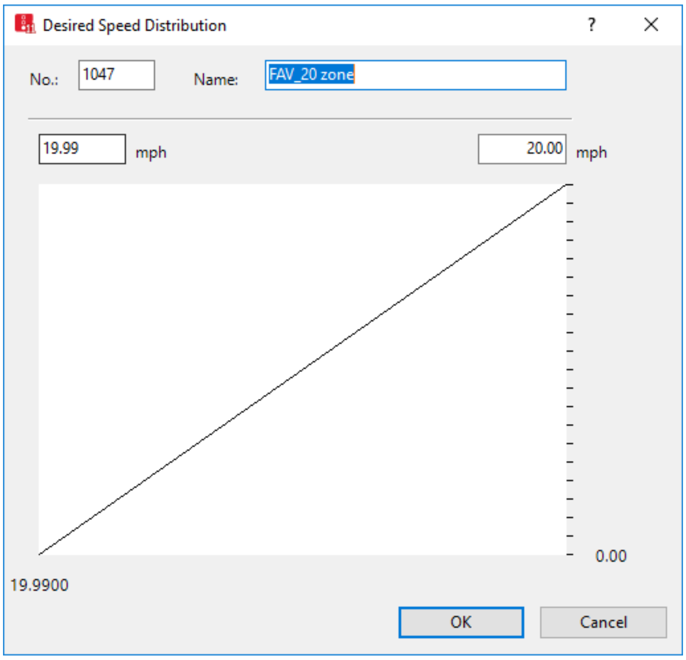


Figure 4-2 Desired speed Distribution for ConFAVs in 20mph zones

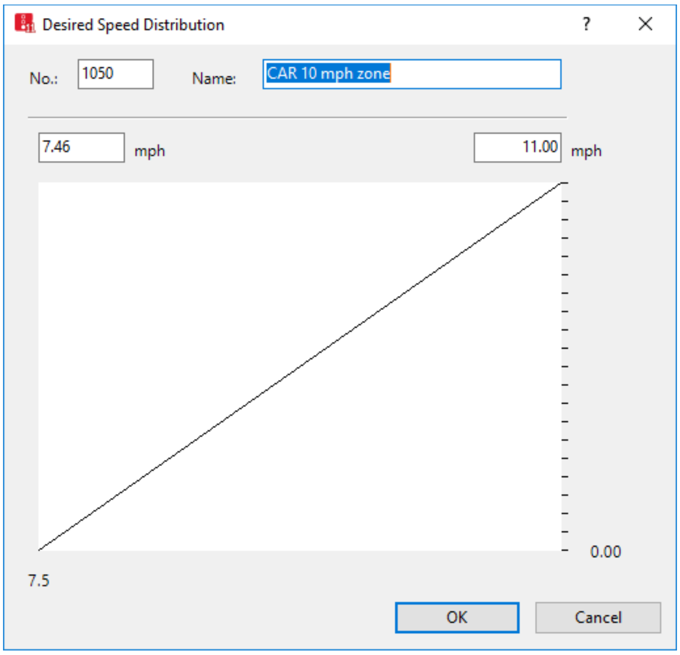


Figure 4-3: Desired speed Distribution for conventional cars in reduced speed zone

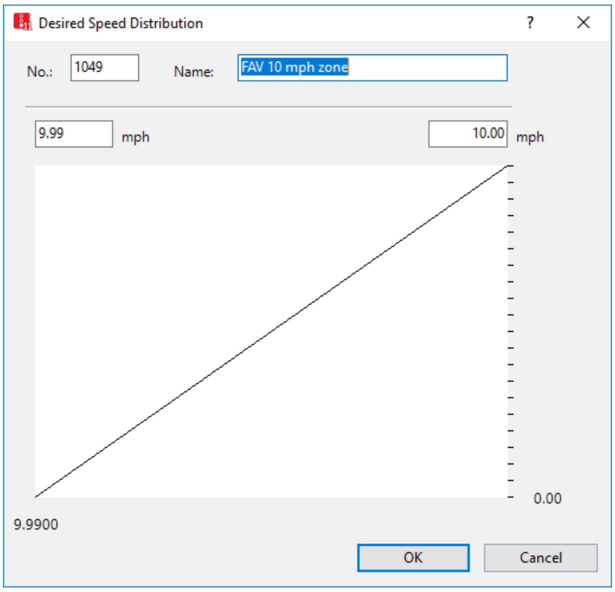


Figure 4-4 Desired speed Distribution for ConFAVs in reduced speed zones

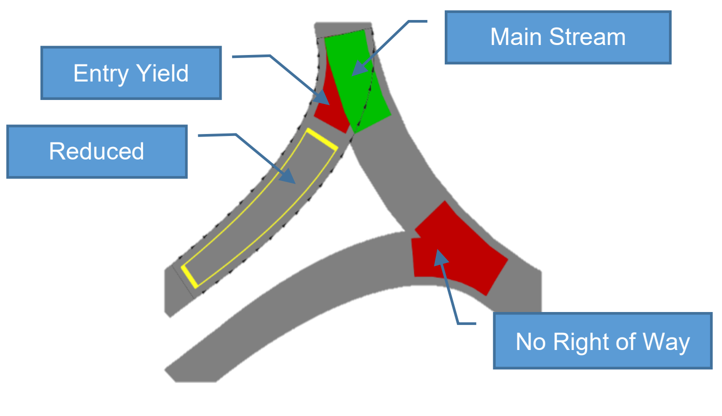
Modelling Right of way using conflict zones:

Conflict zones were used to model right of way in this junction, as it reflects the driving behaviour better than priority rules. Vehicles will plan ahead on how to traverse the conflict areas. For example, a yielding vehicle entering the main stream will decide to either accelerate in order to clear the conflict zone, or to stop if the zone cannot be cleared in time without disrupting oncoming traffic. The vehicle will also calculate is the downstream traffic will interfere with how quickly it will cross the conflict zone, and account for this in the calculation of the time it will take to clear the conflict area (PTV Group, 2018).

Table 4-3: Modelling conflict zones

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
RB: Main Stream	100%	NW - Entry	100%	Link 2 waits
RB: Main Stream	100%	E - Entry	100%	Link 2 waits
RB: Main Stream	100%	SW - Entry	100%	Link 2 waits
RB: Main Stream	100%	SW - Exit	100%	No ROW
RB: Main Stream	100%	NW - Exit	100%	No ROW
RB: Main Stream	100%	E - Exit	100%	No ROW

Table 4-4 Example of entry/exit conflict points and deceleration rates



Vehicle Class	Desire Speed Distribution	Deceleration
Car	10 mph zone	2.00
ConFAV	10 mph zone	2.00

4.2.2 <u>Simulating the Priority Junction</u>

Like the roundabout junction in the previous experiment, a minor road (TA 79/99 class UAP4) joins a major link (TA 79/99 class UAP3). This time traffic on the major link has got priority. Traffic flow between Arms 1 and 2 have priority, as well as those vehicles turning left from Arm 2 into arm 3 (indicated by green in Figure 4-5 below). Vehicles traveling down from arm 1 to turn into arm 3 must wait for northbound traffic from Arm 2 to pass before making a right turn (indicated by yellow in the diagram below). All traffic leaving arm 3 must give way to other vehicles before entering the junction.

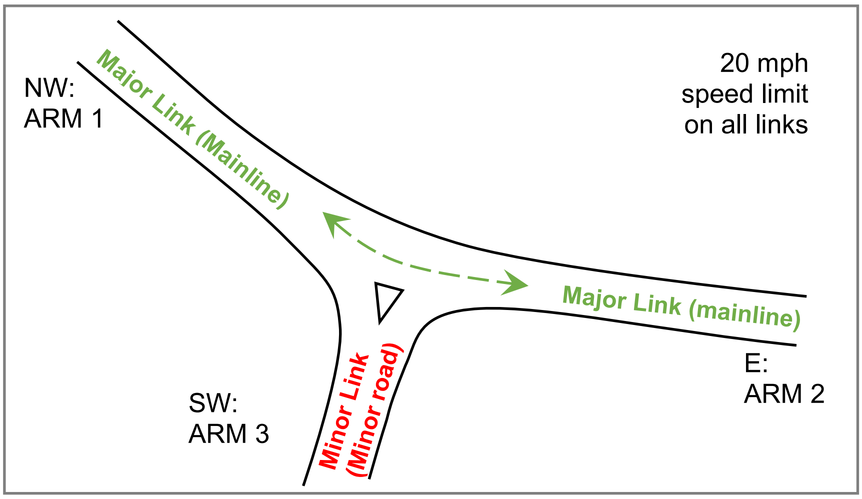


Figure 4-5: Major vs Minor Link

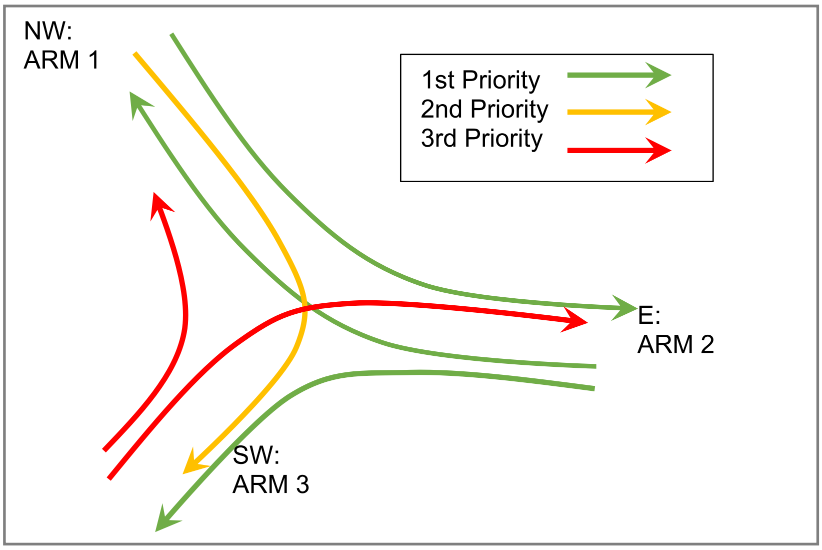


Figure 4-6: Priority of movements

Vehicle input and route decisions

For the simulation, it was assumed that 600 vehicles will enter the network per hour from the NW and SW arm. As shown in the table below, 70% of vehicles will continue along the major link, from NW to E and vice versa, 25% will turn into the minor road (SW arm) and 5% will turn back by making a U-turn in the junction. The minor link will only have 150 vehicles entering per hour, 45% of which will turn left, 45% turn right and 5% will U-turn to leave the junction.

Table 4-5: Priority Junction Route decisions

ARM	Veh Input Volume	Flow to Capacity Ratio	Route Decision
1: NW Major Link	600 Vehs/hr	0.46	SW : E : u-Turn 70% : 25% : 5%
2: E Major Link	600 Vehs/hr	0.46	SW : NW : u-Turn 25% : 70% : 5%
3: SW Minor Link	150 Vehs/hr	0.13	E : NW : u-Turn 45% : 45% : 10%

Desired Speed distribution and Reduced Speed Zones:

The speed distribution is distributed as shown in Table 4-6 below.

Table 4-6 Speed distributions for 20mph zone

Conventional Vehicles		Connected FAVs	
Speed (miles per hour)	Distribution	Speed (miles per hour)	Distribution
18 mph	0.00	19.99 mph	0.00
20 mph	0.14	20.00 mph	1.00
26 mph	1.00	----	----

Vehicles doing a U-turn are modelled to do so using a lower desired speed distribution of 10 mph, using the same distributions as the reduced speed zones in the previous section, as shown in the table below.

Table 4-7: Desired Speed Distribution for 10mph

Conventional Vehicles		Connected FAVs	
Speed (miles per hour)	Distribution	Speed (miles per hour)	Distribution
7.46 mph	0.00	9.99 mph	0.00
11.00 mph	1.00	10.00 mph	1.00

The deceleration within these reduced speed zones for Fully autonomous car will be the same as conventional cars, which is capped at 2.

Table 4-8: Reduced Speed zones

Vehicle Class	Desire Speed Distribution	Deceleration
Car	10 mph U-Turn	2.00
ConFAV	10 mph FAV U-Turn	2.00

<u>Vehicle Composition and Relative Flow:</u>

The model was run at 20% iterations. The penetration rate of the fully autonomous vehicle was modelled using the relative flow distribution table shown below.

Table 4-9: Vehicle composition and relative flow distribution

FAV %	Vehicle Type	Desire Speed Distribution	Relative Flow
0% FAV Penetration	Car	Car 20 mph zone	1.000
	ConFAV	FAV 20 zone	0.000
20% FAV Penetration	Car	Car 20 mph zone	0.800
	ConFAV	FAV 20 zone	0.200
40% FAV Penetration	Car	Car 20 mph zone	0.600
	ConFAV	FAV 20 zone	0.400
60% FAV Penetration	Car	Car 20 mph zone	0.400
	ConFAV	FAV 20 zone	0.600
80% FAV Penetration	Car	Car 20 mph zone	0.200
	ConFAV	FAV 20 zone	0.800
100% FAV Penetration	Car	Car 20 mph zone	0.000
	ConFAV	FAV 20 zone	1.000

Modelling Right of way using conflict zones:

This junction is not controlled by signals, and so vehicle priority was modelled using conflict zones. Vehicles on the same link, mutually observe each other, and so only those that cross each other paths were considered in this experiment. The software manual indicates that controlling junction priority by modelling conflict zones, as this has a clearer indication of natural driving behaviour (PTV Group, 2018).

Branching Conflicts

In branching conflicts, all vehicles acknowledge each other but there is no right of way (R.O.W.), and vehicles remain in their original sequence.

Figure 4-7: NW Arm 1 Branching Conflict

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW – SW	100%	NW – E	100%	No ROW
NW – SW	100%	NW U-Turn	100%	No ROW
NW – E	100%	NW U-Turn	100%	No ROW

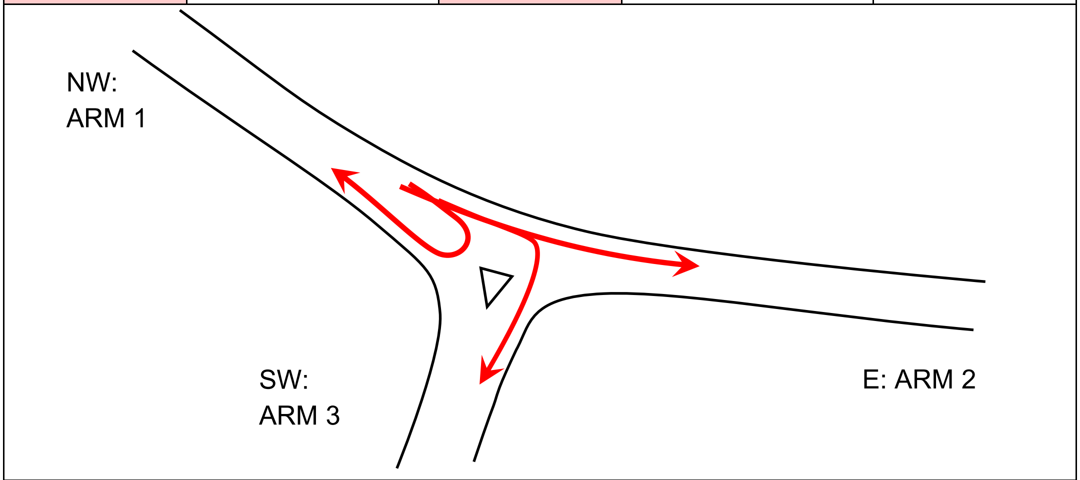


Figure 4-8: E Arm 2 Branching Conflict

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
E U-Turn	100%	E – NW	100%	No ROW
E U-Turn	100%	E – SW	100%	No ROW
E – NW	100%	E – SW	100%	No ROW

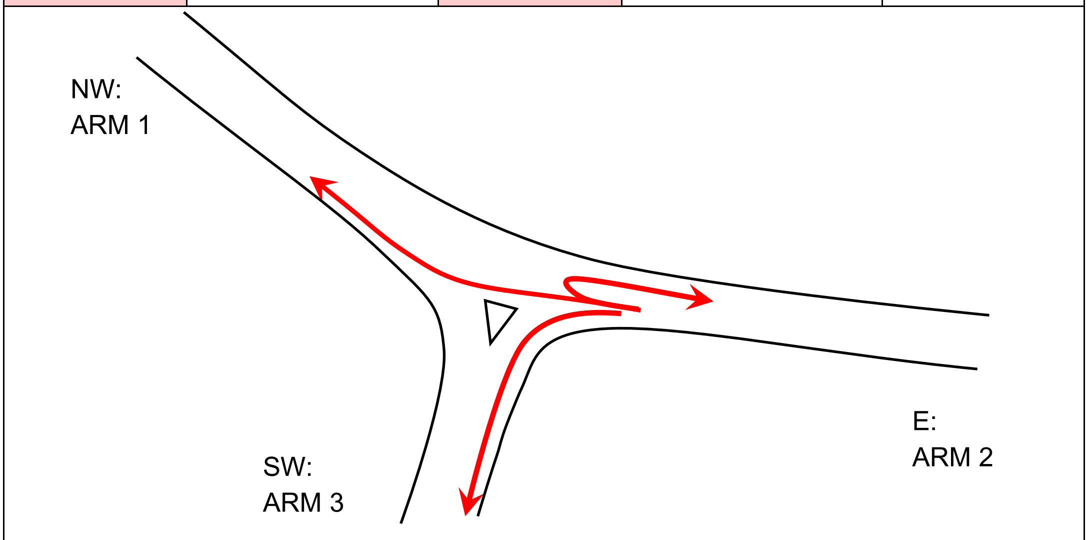
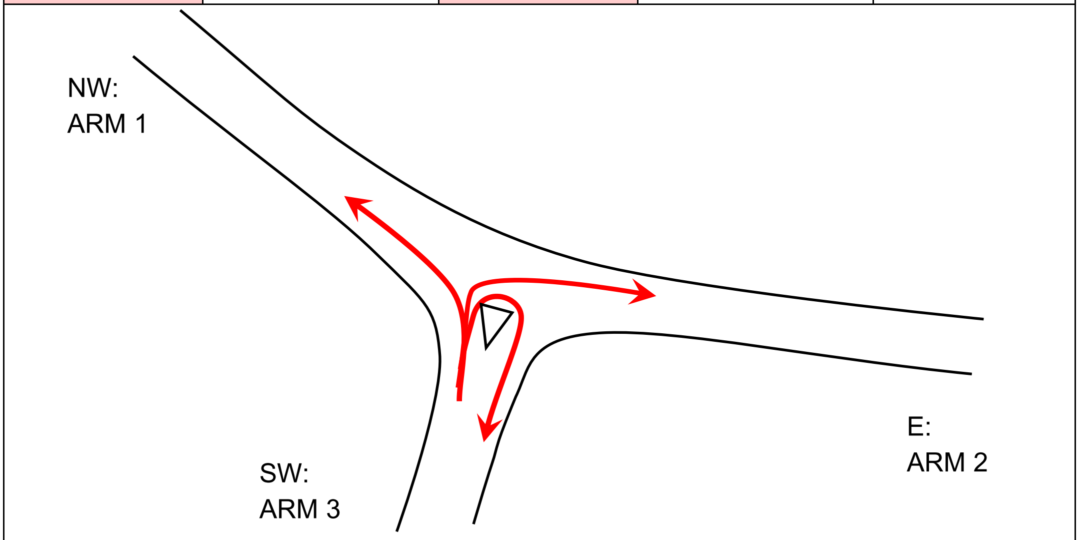


Figure 4-9: SW Arm 3 Branching Conflict

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
SW U-Turn	100%	SW – E	100%	No ROW
SW U-Turn	100%	SW – NW	100%	No ROW
SW – E	100%	SW – NW	100%	No ROW



Other Conflicts

In all other conflicts, the right of way (R.O.W.) is calculated based on giving the main flow traffic priority over the minor flow, as shown in **Error! Reference source not f ound.** to **Error! Reference source not found.**.

Table 4-10: Modelling other conflicts

No.	Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
1	NW – SW	100%	SW U-turn	100%	Link 2 waits
2	NW – E	100%	E U-turn	100%	Link 2 waits
3	NW – SW	100%	SW – E	100%	Link 2 waits
4	NW – E	100%	SW – E	100%	Link 2 waits
5	NW U-turn	100%	SW – NW	100%	Link 2 waits
6	E U-turn	100%	SW – E	100%	Link 2 waits
7	E – NW	100%	SW – NW	100%	Link 2 waits
8	NW – SW	100%	E – NW	100%	Link 1 waits
9	NW U-turn	100%	E – NW	100%	Link 1 waits
10	SW – E	100%	E – NW	100%	Link 1 waits
11	NW – SW	100%	E – SW	100%	Link 1 waits
12	SW U-turn	100%	E – SW	100%	Link 1 waits

Figure 4-10: Other conflict 1

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW – SW	100%	SW U-turn	100%	Link 2 waits

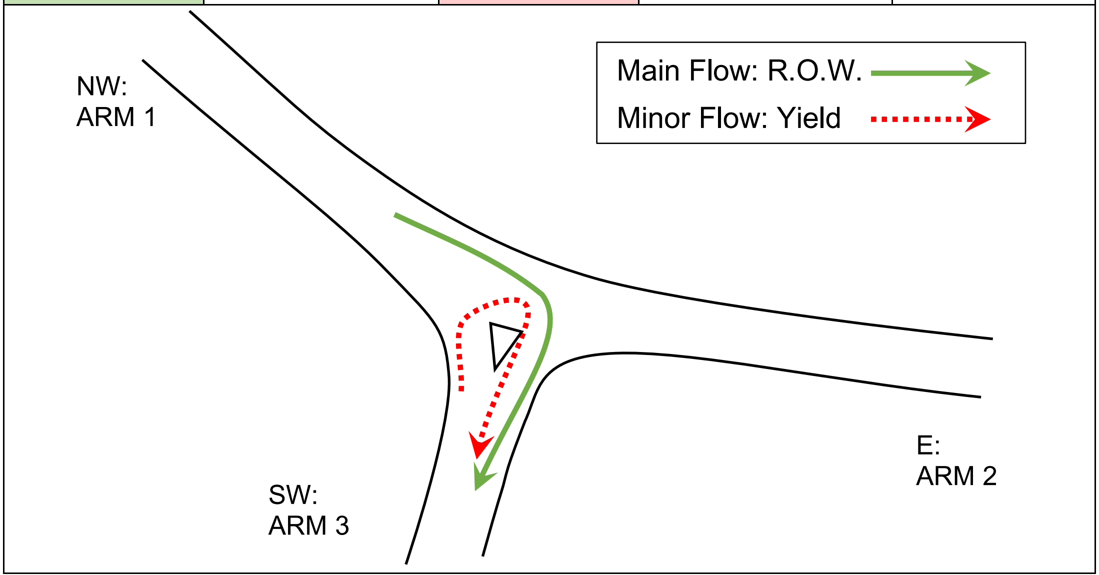


Figure 4-11: Other conflict 2

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW – E	100%	E U-turn	100%	Link 2 waits

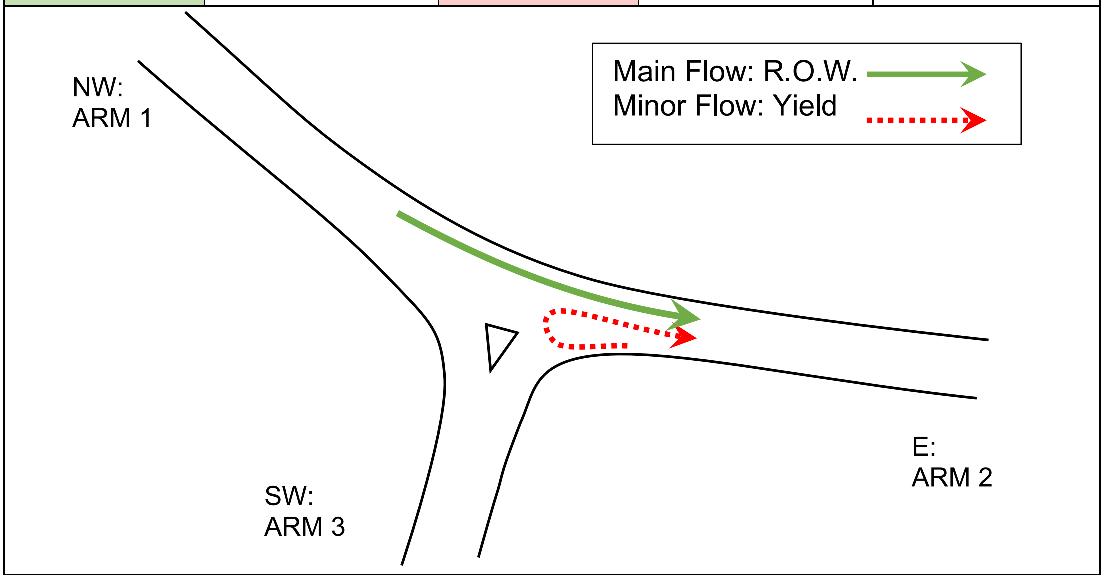


Figure 4-12: Other conflict 3

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW – SW	100%	SW – E	100%	Link 2 waits

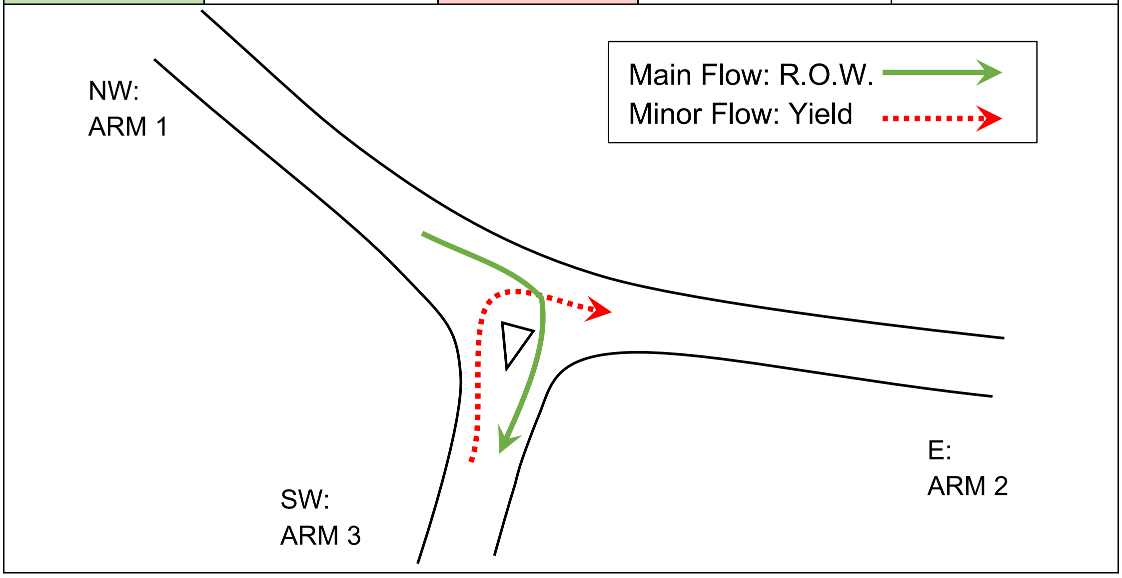


Figure 4-13: Other conflict 4

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW – E	100%	SW – E	100%	Link 2 waits

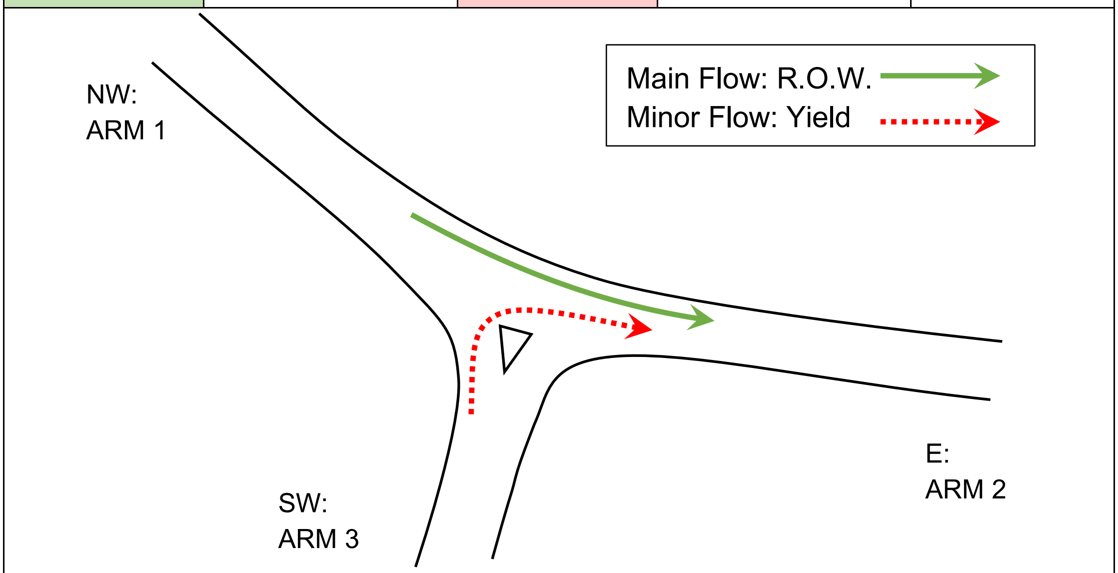


Figure 4-14: Other conflict 5

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW U-turn	100%	SW – NW	100%	Link 2 waits

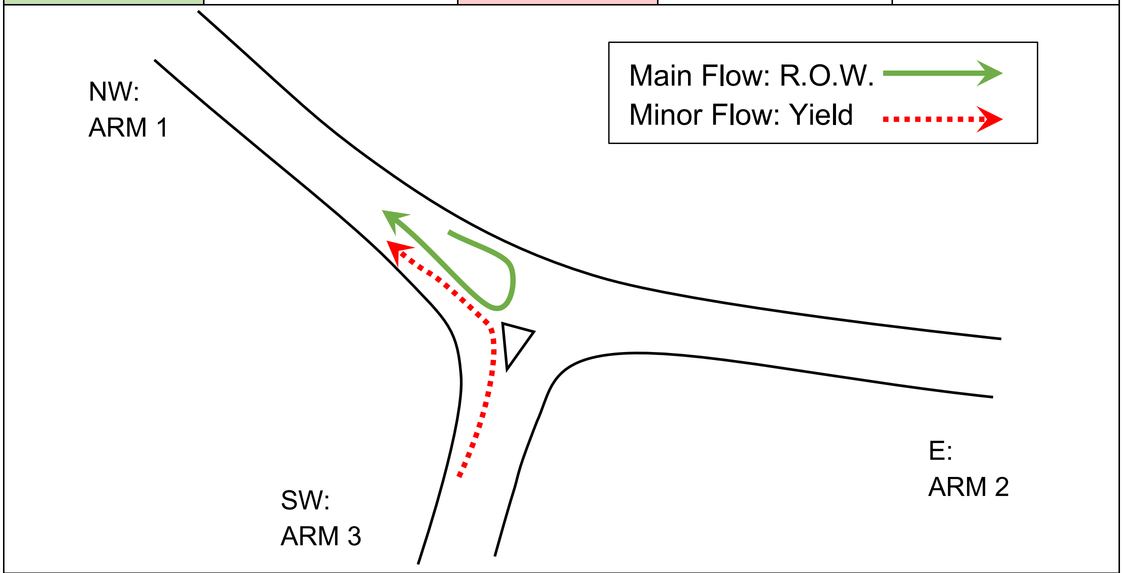


Figure 4-15: Other conflict 6

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
E U-turn	100%	SW – E	100%	Link 2 waits

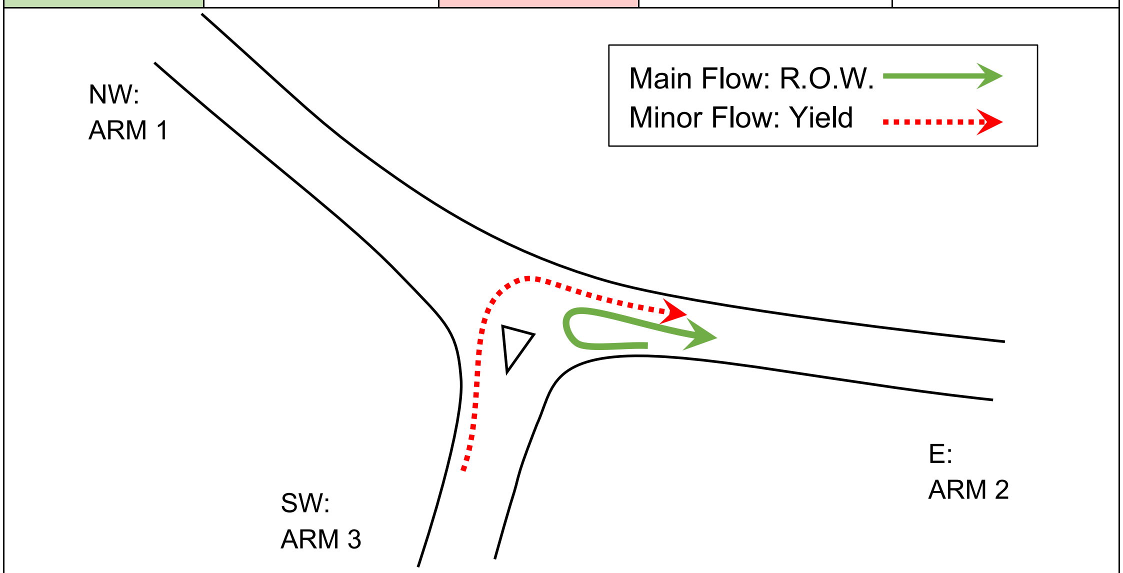


Figure 4-16: Other conflict 7

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
E – NW	100%	SW – NW	100%	Link 2 waits

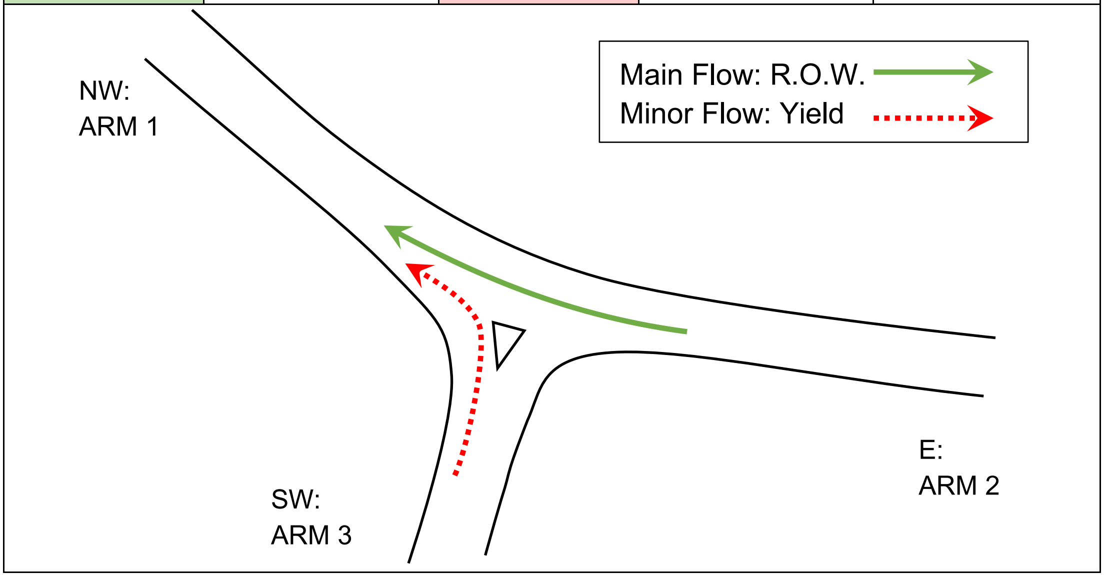


Figure 4-17: Other conflict 8

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW – SW	100%	E – NW	100%	Link 1 waits

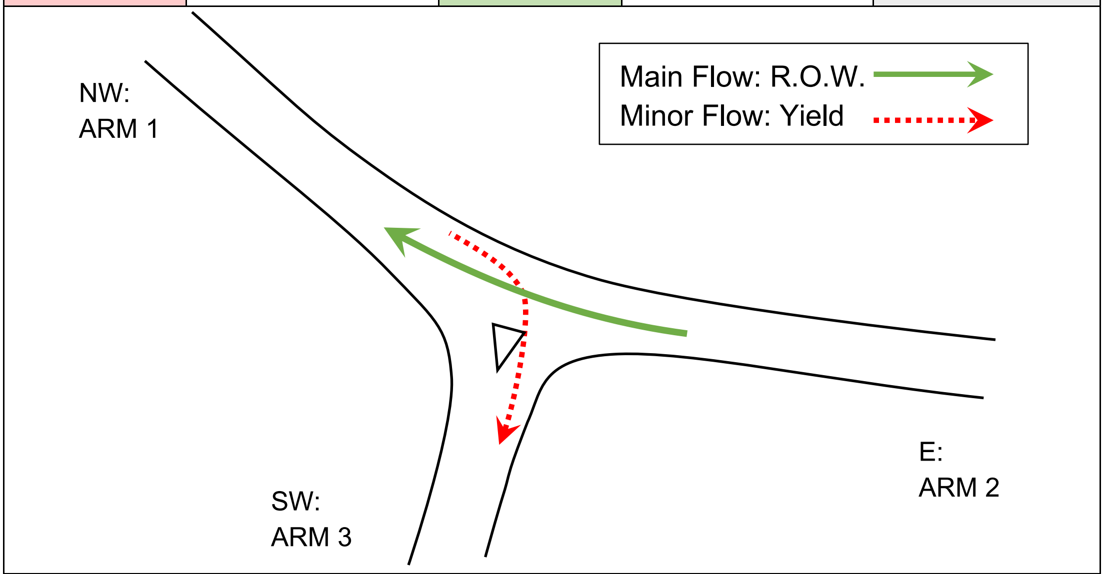


Figure 4-18: Other conflict 9

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW U-turn	100%	E – NW	100%	Link 1 waits

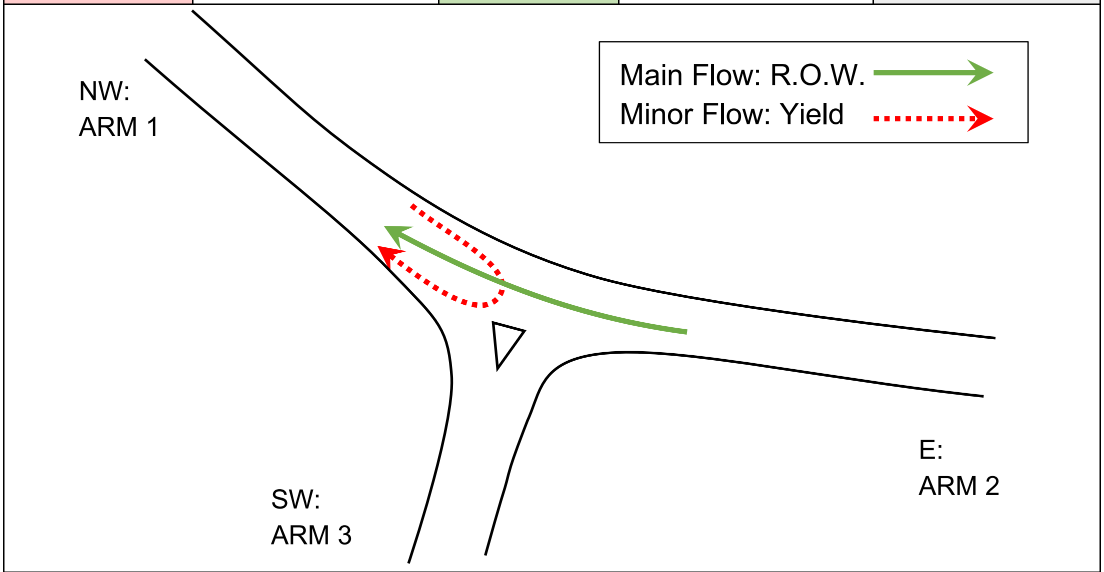


Figure 4-19: Other conflict 10

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
SW – E	100%	E – NW	100%	Link 1 waits

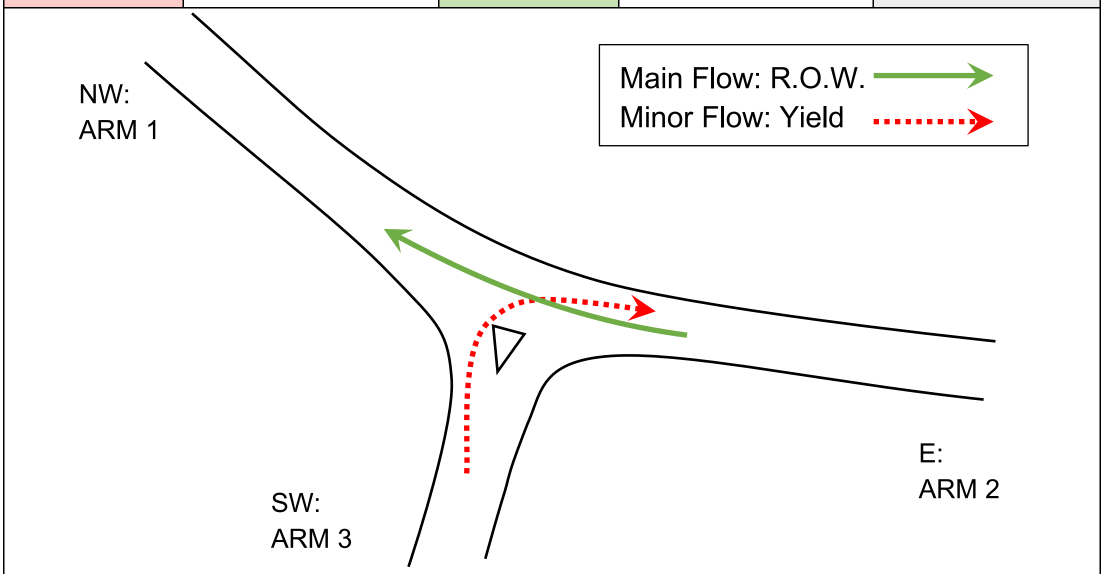


Figure 4-20: Other conflict 11

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW – SW	100%	E – SW	100%	Link 1 waits

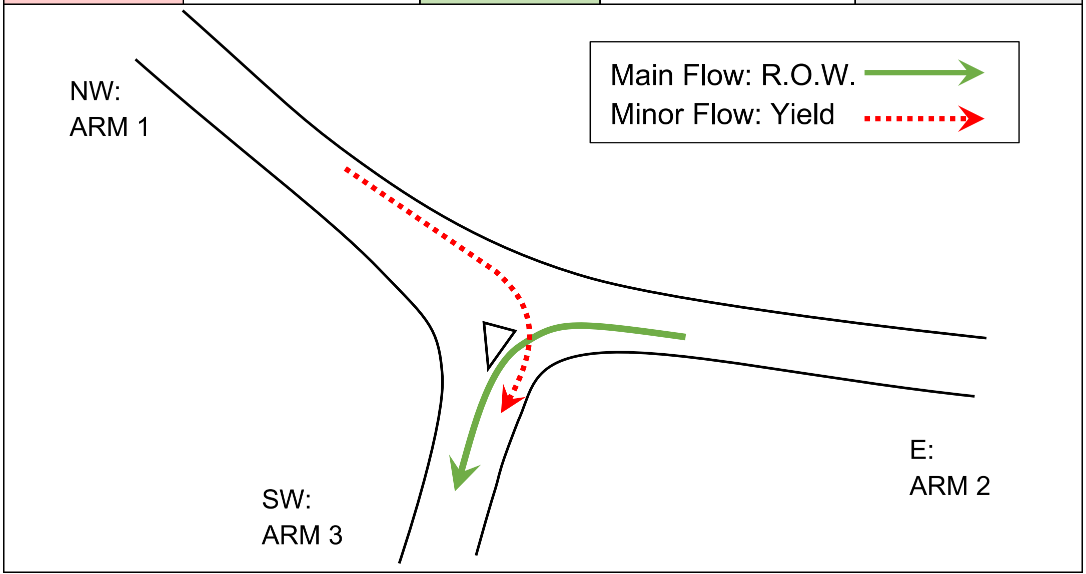
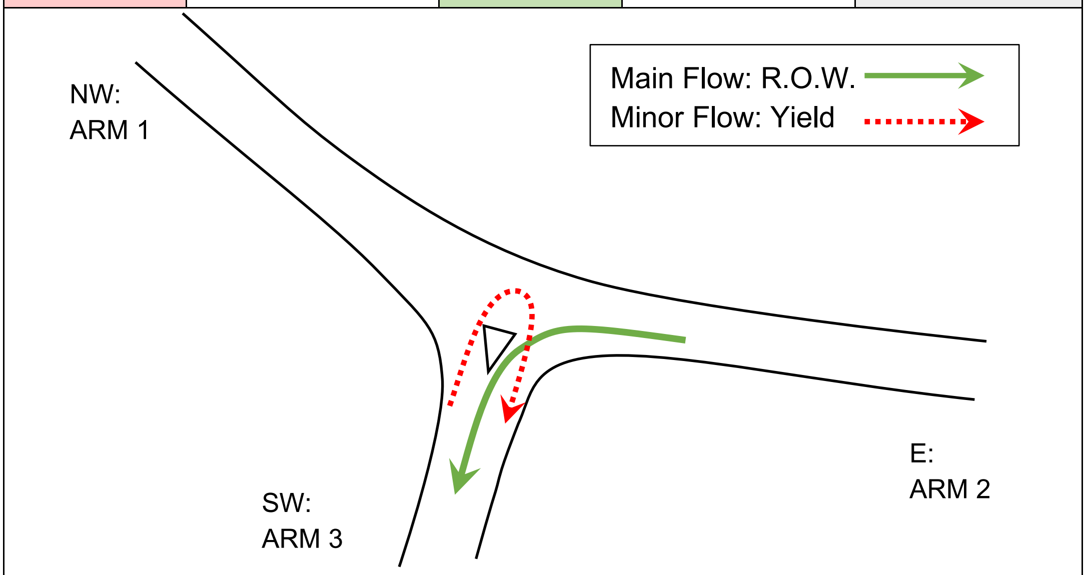


Figure 4-21: Other conflict 12

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
SW U-turn	100%	E – SW	100%	Link 1 waits



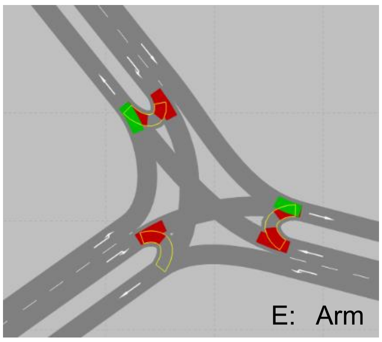
4.2.3 Simulating the Signal Controlled Junction

In this experiment, the Southwest arm (SW: Arm 3) was a minor link (TA 79/99 class UAP4) that joined with a major road (TA 79/99 class UAP3) running from Northwest (NW: Arm 1) to east (E: Arm 2). The junction type considered was a roundabout. The junction is in a built up area, so the speed limit applied to all roads were 20 miles per hour (mph). Each arm entering the intersectio was designed with two lanes, allowing through traffic to be unterupted by turning traffic, as well as allowing arms to be split into two different signal phases.

Vehicle Input and Route Decisions:

The following table shows the vehicle flow input and route decisions for each arm of the junction:

Table 4-11: Signal-controlled Route Decisions

<table>
<tr><td rowspan="7">NW: Arm 1

SW: Arm 3</td><th>ARM</th><th>Veh Input Vol</th><th>Flow to Capacity Ratio</th><th>Route Decision</th></tr>
<tr><td rowspan="2">1: NW Major Link</td><td rowspan="2">600 Vehs/hr</td><td rowspan="2">0.46</td><td>SW : E : u-Turn</td></tr>
<tr><td>70% : 25% : 5%</td></tr>
<tr><td rowspan="2">2: E Major Link</td><td rowspan="2">600 Vehs/hr</td><td rowspan="2">0.46</td><td>SW : NW : u-Turn</td></tr>
<tr><td>25% : 70% : 5%</td></tr>
<tr><td rowspan="2">3: SW Minor Link</td><td rowspan="2">150 Vehs/hr</td><td rowspan="2">0.13</td><td>E : NW : u-Turn</td></tr>
<tr><td>45% : 45% : 10%</td></tr>
</table>

Vehicle Composition and Relative Flows:

The model was run at 20% iterations. The penetration rate of the fully autonomous vehicle was modelled using the relative flow distribution table shown below.

Table 4-12: Vehicle composition and relative flow distribution table

FAV %	Vehicle Type	Desire Speed Distribution	Relative Flow
0% FAV Penetration	Car	Car 20 mph zone	1.000
	ConFAV	FAV 20 zone	0.000
20% FAV Penetration	Car	Car 20 mph zone	0.800
	ConFAV	FAV 20 zone	0.200
40% FAV Penetration	Car	Car 20 mph zone	0.600
	ConFAV	FAV 20 zone	0.400
60% FAV Penetration	Car	Car 20 mph zone	0.400
	ConFAV	FAV 20 zone	0.600
80% FAV Penetration	Car	Car 20 mph zone	0.200
	ConFAV	FAV 20 zone	0.800
100% FAV Penetration	Car	Car 20 mph zone	0.000
	ConFAV	FAV 20 zone	1.000

Desired Speed Distribution:

The speed distribution is of major importance, as this has a direct connection to link capacity and average travel times. It is programmed within the software that is there are no hindrances such as signal controls or other road users, the driver will travel at its desired speed. The area in consideration is assumed to be built up and as such the speed on the link is limited to 20 mph and are distributed as shown in the table below.

Table 4-13 Speed distributions for 20mph zone

Conventional Vehicles		Connected FAVs	
Speed (miles per hour)	Distribution	Speed (miles per hour)	Distribution
18 mph	0.00	19.99 mph	0.00
20 mph	0.14	20.00 mph	1.00
26 mph	1.00	----	----

Like the previous junctions, vehicles doing a U-turn are modelled to do so using a lower desired speed distribution of 10 mph, using the same distributions as the reduced speed zones in the previous section, as shown in the table below.

Table 4-14: Desired Speed Distribution for 10mph

Conventional Vehicles		Connected FAVs	
Speed (miles per hour)	Distribution	Speed (miles per hour)	Distribution
7.46 mph	0.00	9.99 mph	0.00
11.00 mph	1.00	10.00 mph	1.00

The deceleration within these reduced speed zones for Fully autonomous car will be the same as conventional cars, which is capped at 2.

Table 4-15: Reduced Speed zones

Vehicle Class	Desire Speed Distribution	Deceleration
Car	10 mph U-Turn	2.00
ConFAV	10 mph FAV U-Turn	2.00

Modelling Right of way using Signals

The junction is governed by a 60-second cycle length over 6 signal groups. At any point in time, three signal groups will be running concurrently with each other as show in the image below. This is to allow the uninterrupted flow of traffic along certain routes.

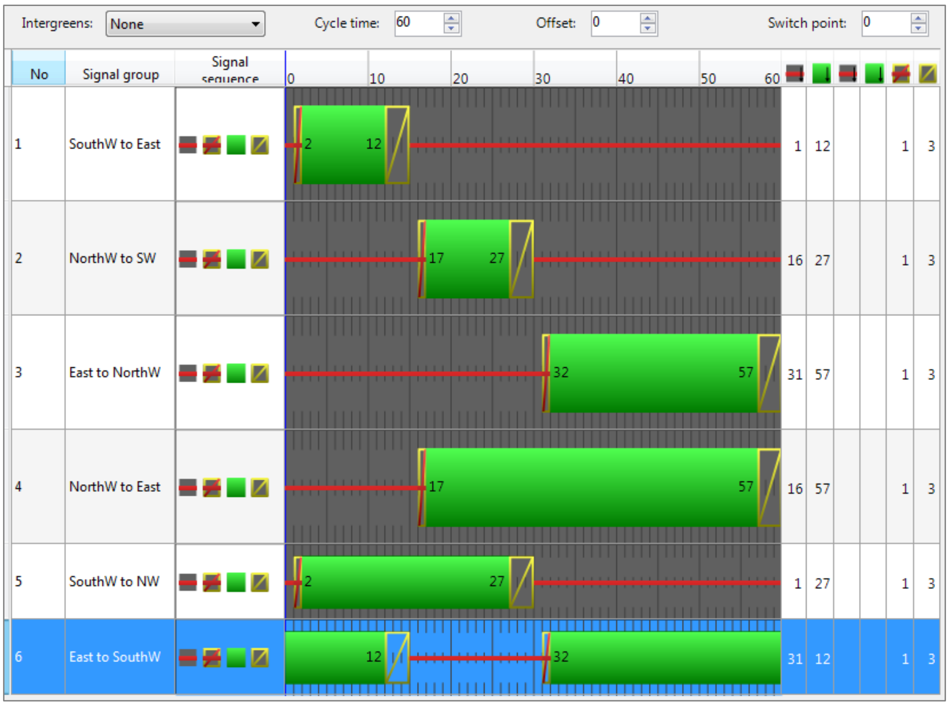


Figure 4-22: Signal Program for 60 Phase Cycle

Table 4-16: Minimum sequence durations for signal groups

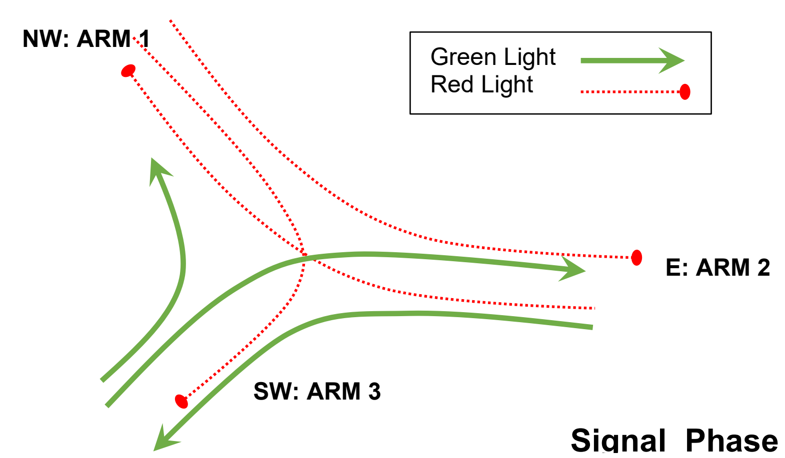
	Red	*Amber & Red*	*Green*	*Amber*
SouthW to East	46	1	10	3
NorthW to SouthW	46	1	10	3
East to NorthW	31	1	25	3
NorthW to East	16	1	40	3
SouthW to NW	31	1	25	3
East to SouthW	16	1	40	3

Sequence Timing for Phase 1

During this signal phase, the East arm will still have a left green arrow for another 12 seconds (40 seconds in total) that started in Phase 3, while through traffic from that arm was on red. The Southwest arm had green to go in any direction. While the right turning traffic from the south west arm changed to amber, the left turning traffic maintained a green arrow to continue into phase 2. The timings for the sequences are shown in the figure below.

Table 4-17 Minimum sequence durations for Signal Phase 1

	Red	*Amber & Red*	*Green*	*Amber*
SouthW to East	1	1	10	3
East to SW continuing from Phase 3	12			3
Southwest to NorthW	1	1	13	

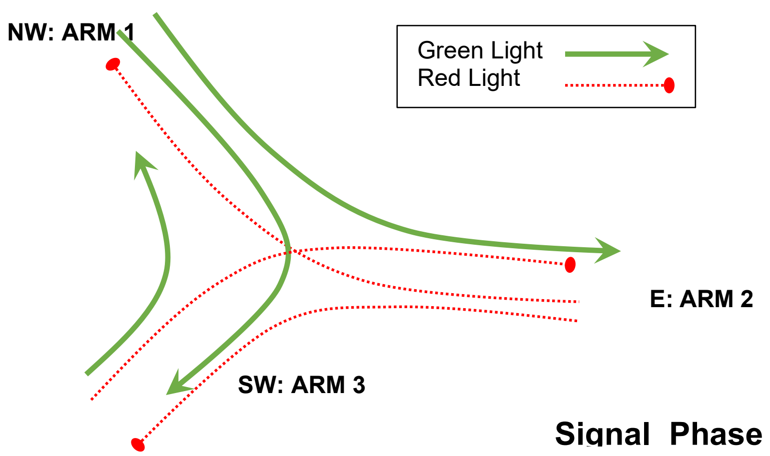


Sequence timing for Phase 2

During this signal phase, the Northwest arm had a right turn green arrow for southwest-bound traffic, while eastbound traffic from that arm maintained a green signal after the right turn arrow changes to amber. Left turning traffic from the Southwest arm still had a green arrow for another 12 seconds (25 seconds in total) to turn left from the previous phase but changed to amber the same time as the right turning traffic from the northwest arm. The eastbound traffic from the Northwest arm started in this phase to then end in phase 3. The timings for the sequences are shown in the figure below.

Table 4-18 Minimum sequence durations for Signal Phase 2

	Red	*Amber & Red*	*Green*	*Amber*
NorthW to SouthW	1	1	10	3
SW to NW continuing from Phase 2	12			3
NW to East	1	1	13	

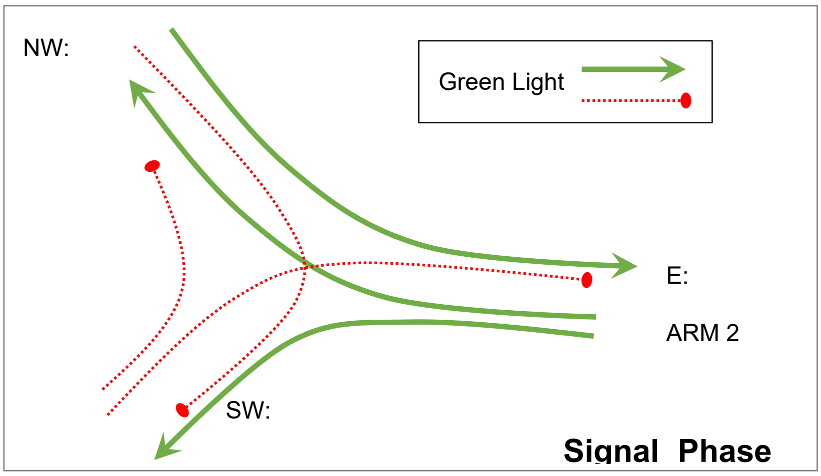


__Sequence timing for Phase 3__

Phase 3 managed traffic leaving the eastern arm, including Northwest-bound and Southwest-bound traffic. The left turning traffic got its green in this phase but gets red at the end of the next phase during which the 60 second cycle restarted with phase 1. All eastbound traffic from the Northwest arm still had green for another 27 seconds (40 seconds in total for green) before changing to amber. The timings for the sequences are shown in the figure below.

Table 4-19 Minimum sequence durations for Signal Phase 3

	Red	*Amber & Red*	*Green*	*Amber*
East to NorthW	1	1	25	3
NW to East continuing from Phase 2	27			3
East to SW	1	1	28	



Modelling Conflict zones during Signal Phases

While this is a signal-controlled junction, there is expected to be some conflict zones during each of the light phases. A total of 6 conflicts were identified as detailed below.

Branching Conflicts

In branching conflicts, all vehicles acknowledge each other but there is no right of way (R.O.W.), and vehicles remain in their original sequence.

Figure 4-23: NW Arm 1 Branching Conflict

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW U-Turn	100%	NW – SW	100%	No ROW

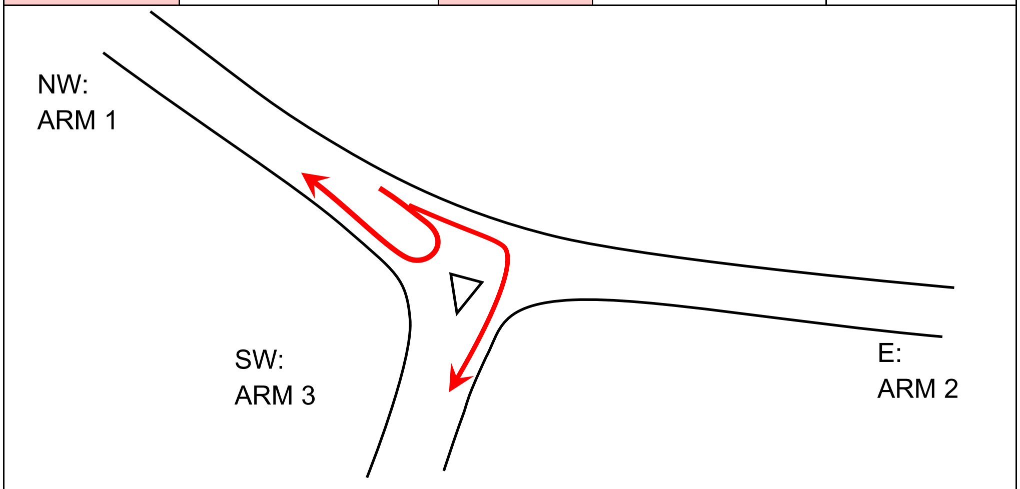


Figure 4-24: E Arm 2 Branching Conflict

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
E U-Turn	100%	E – NW	100%	No ROW

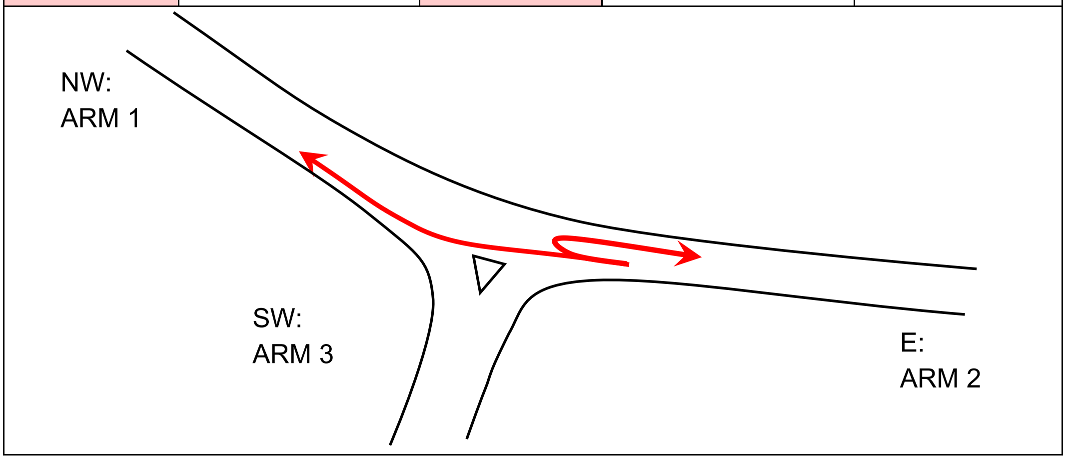
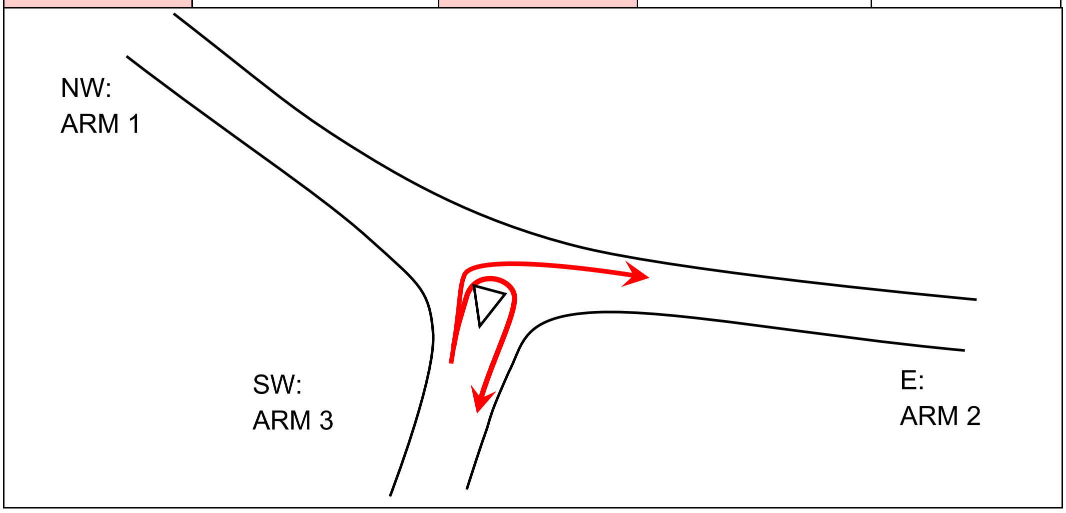


Figure 4-25: SW Arm 3 Branching Conflict

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
SW U-Turn	100%	SW – E	100%	No ROW



Other Conflicts

Other conflicts across the 3 signal phases are expected to arise from U-turns.

Figure 4-26: SW U-turn conflict

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
NW – E	100%	E U-turn	100%	Link 2 waits

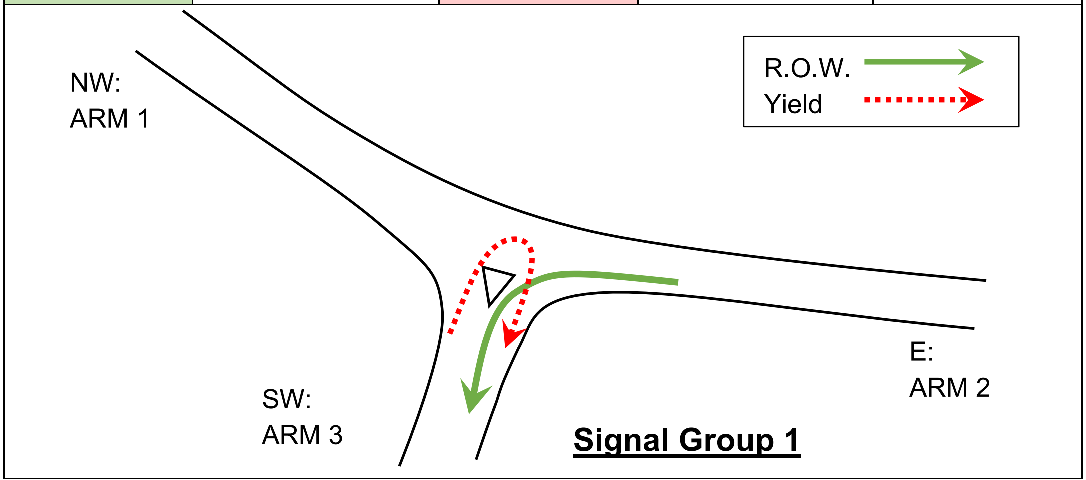


Figure 4-27: NW U-turn conflict

Link 1	Visibility: Link 1	NW U-turn	Visibility: Link 2	Status
SW – NW	100%	NW U-turn	100%	Link 2 waits

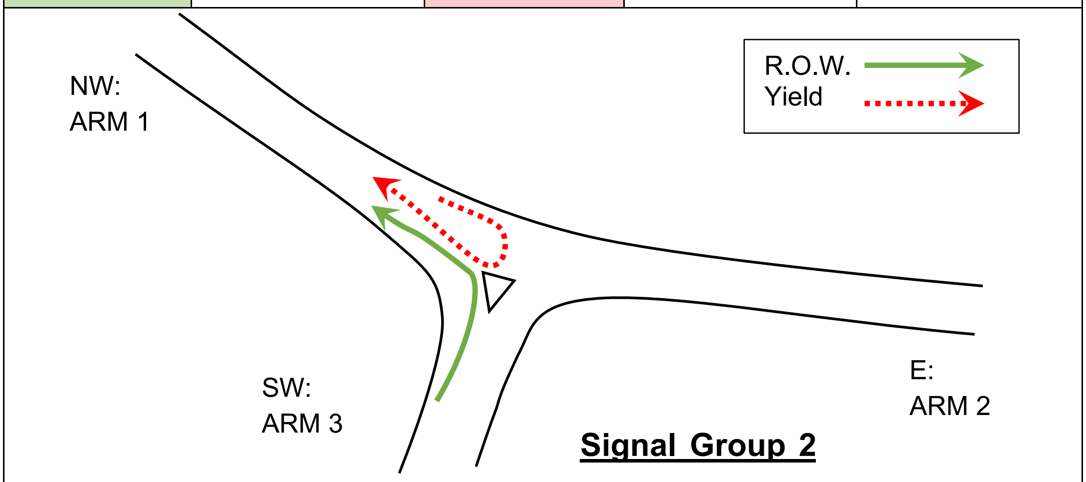


Figure 4-28: East U-turn conflict

Link 1	Visibility: Link 1	Link 2	Visibility: Link 2	Status
SW U-turn	100%	E – SW	100%	Link 1 waits

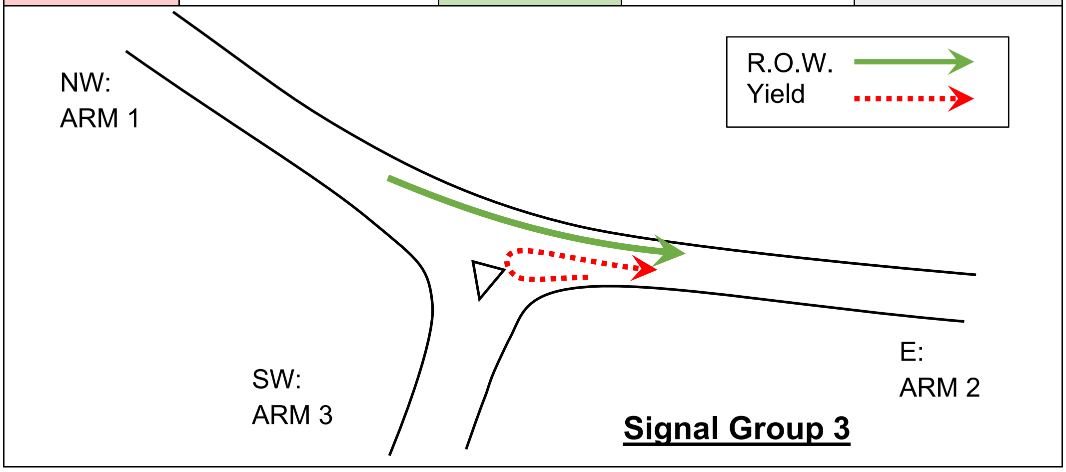


Table 4-20: Reduced Speed zones

Vehicle Class	Desire Speed Distribution	Deceleration
Car	1049: 10 mph zone	2.00
ConFAV	1049: 10 mph zone	2.00

4.3 Findings and Analysis

In this section of the report the results from the simulations of all three junction were collated and discussed. The findings will be broken down and discussed as follows:

- Priority Junction – Congestion Performance
- Signal Controlled Junction – Congestion Performance
- Roundabout – Congestion Performance
- Safety Performance of Behavioural Models
- Summary of Results

4.3.1 Priority Junction – Congestion Performance

Each vehicle route decision was plotted to show the total delay (in seconds) experienced at each level of ConFAV penetration. These were classified as the movements shown in Figure 4-29 below, where a total of nine (9) movements were identified.

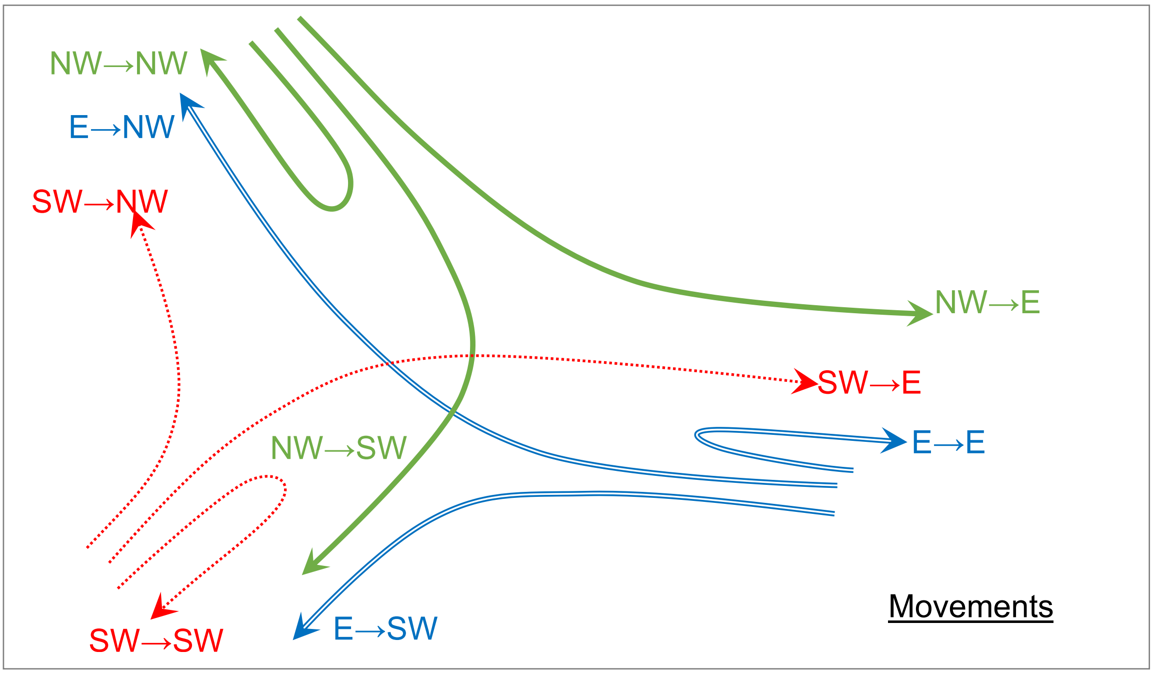


Figure 4-29 Vehicle movements within junction

Results

As previously discussed, the delay of a vehicle on its route choice is calculated by subtracting from its actual travel time a theoretical one in which there were no other vehicles, and/or no signal controls or other reasons for stops to occur (PTV Group, 2018b). In this stage of the research, there were no public passenger vehicle, or allocated parking, so the delay due to braking before a PT stop and/or subsequent acceleration after a PT stop was not a factor in the calculation of the delay. Travel time was defined as a measurement parameter so that the software could make this calculation. The performance of each model for each route are plotted in the graphs shown in Figure 4-30 to Figure 4-34 below. The summary of results is discussed on page 118.

The ratio of flow to capacity (RFC) for each of the models were kept the same for 0% ConFAV penetration (100% conventional vehicles). The movement of making a right turn from the minor road (0.13 RFC) to the mainline (0.46 RFC) shown in Figure 4-30 below had a mediocre LOS category C (where delay >15s to 25s). This is seen to improve with the introduction of ConFAVs, dropping to a LOS of category A (where delay >10s).

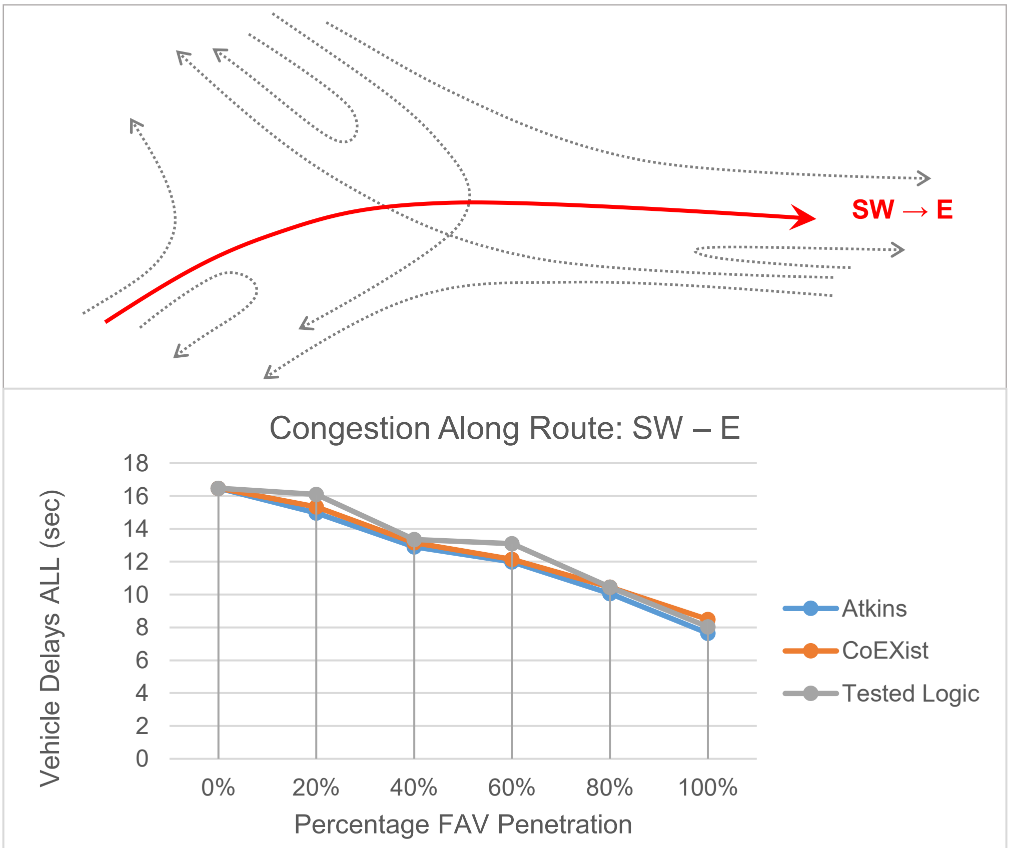


Figure 4-30: Congestion on Route SW - E

The movement of conducting a u-turn in the junction from the minor road (0.13 RFC) showed a good level of service (LOS) of category B (where delay >10s to 15s) when there was 0% ConFAVs in the network. LOS was observed to improve with the introduction of ConFAVs, dropping to the excellent LOS of category A (where delay >10s) as seen in Figure 4-31 below.

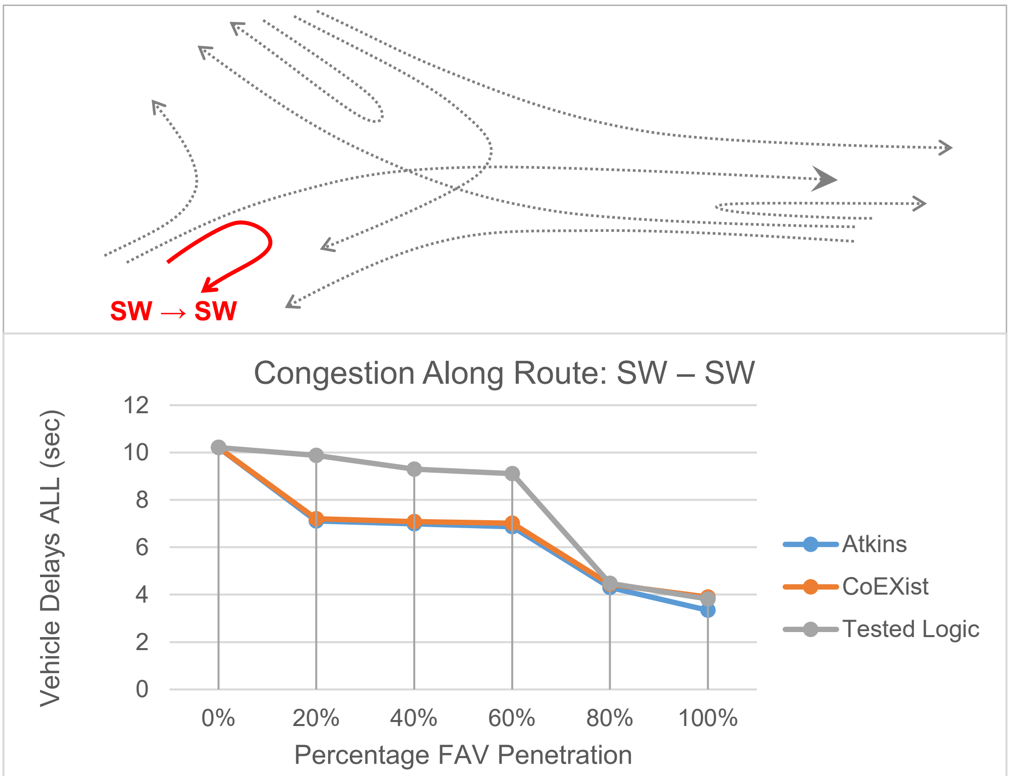


Figure 4-31: Congestion on Route SW - SW

The movement of making a left turn from the minor road (0.13 RFC) to the mainline (0.46 RFC) showed an excellent level of service (LOS) of category A (where delay >10s) when there was 0% ConFAVs in the network. Figure 4-32 below shows that LOS continued to improve as the introduction of ConFAVs resulted in the reduction of recorded delay.

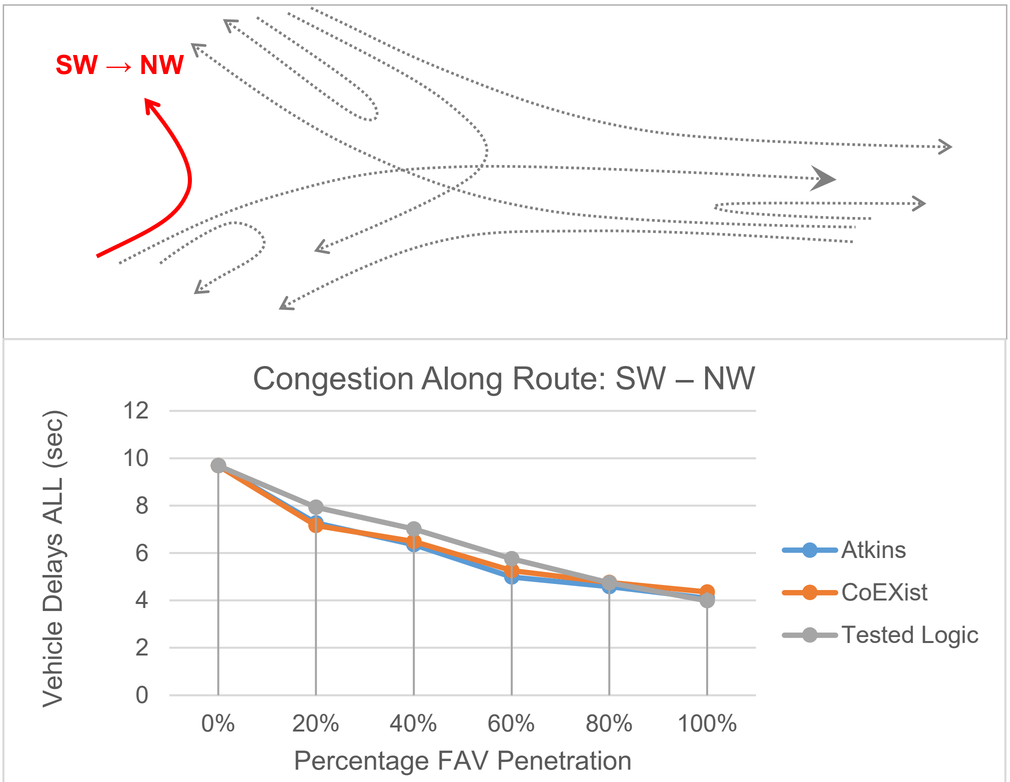


Figure 4-32: Congestion on Route SW - NW

The movements of making a U-turn on the mainline (46 RFC) showed an excellent level of service (LOS) of category A (where delay >10s) when there was 0% ConFAVs in the network. Figure 4-33 and Figure 4-34 overleaf shows that LOS improve with the introduction of ConFAVs, as recorded delay decreased.

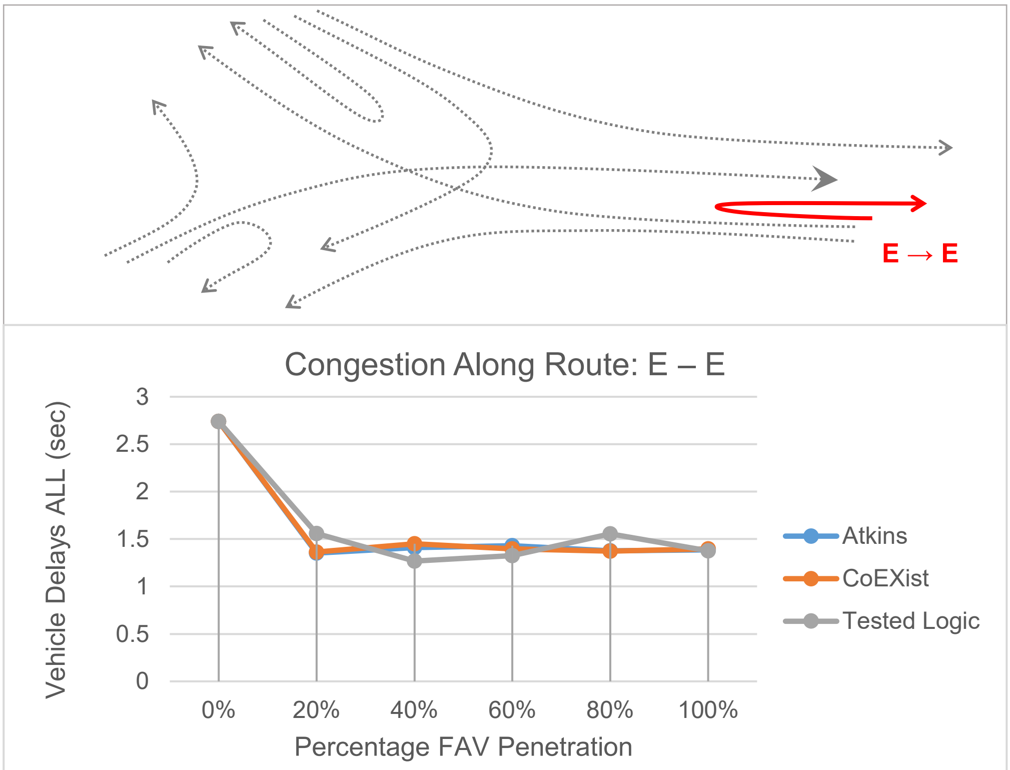


Figure 4-33: Congestion on Route E – E

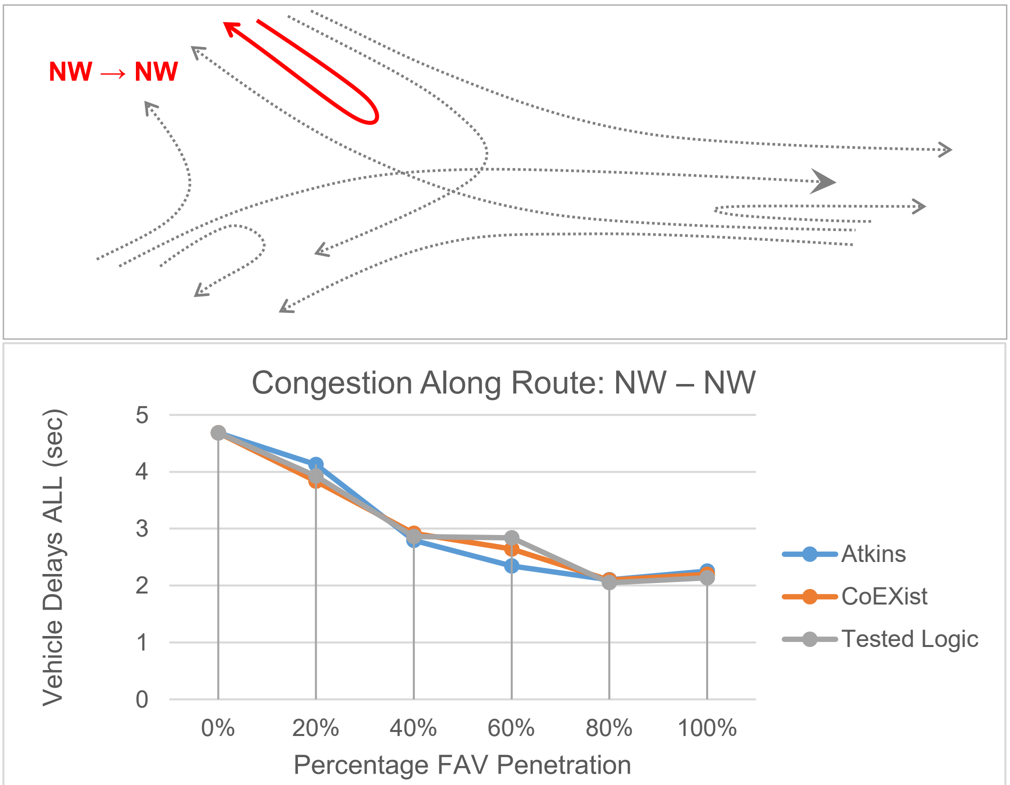


Figure 4-34: Congestion on Route NW - NW

The 2 free flow movements of staying on the mainline (46 RFC) or making a left turn on to the minor road (0.13 RFC) showed an excellent level of service (LOS) of category A (where delay >10s) when there was 0% ConFAVs in the network. The following Figure 4-35, Figure 4-36, and Figure 4-37 show that LOS improve with the introduction of ConFAVs, as recorded delay decreased.

There may be some initial delay of free-flow traffic movements on the mainline as vehicles slow down to let others turn onto the minor road, or to let others join the mainline. An example of this is Figure 4-37 where an initial delay of approximately 3.5s was recorded at 0% ConFAV penetration, which could be explained by Eastbound vehicles on the mainline slowing down to let those turning right leave the mainline, or let others join in front.

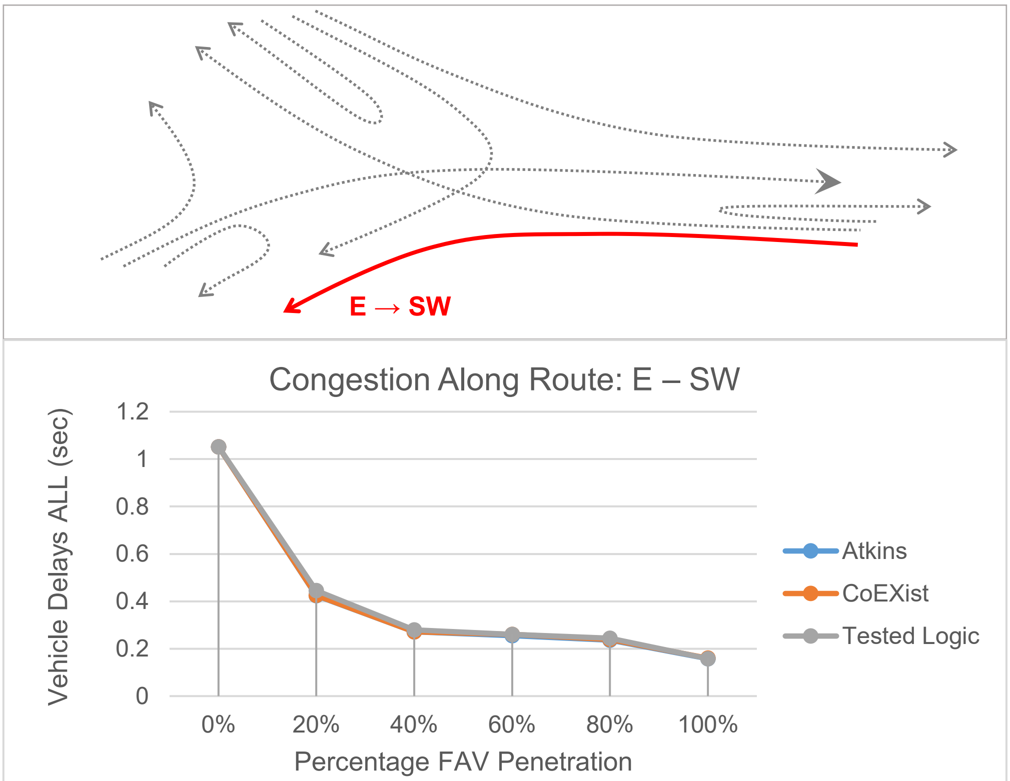


Figure 4-35: Congestion on Route E - SW

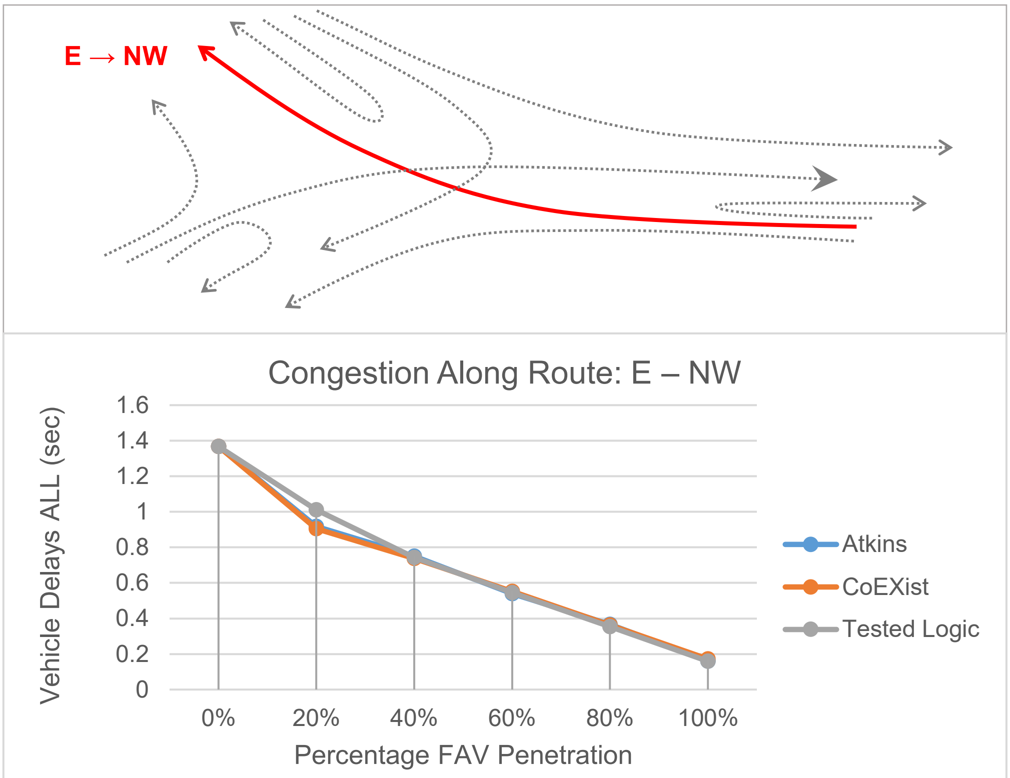


Figure 4-36: Congestion on Route E - NW

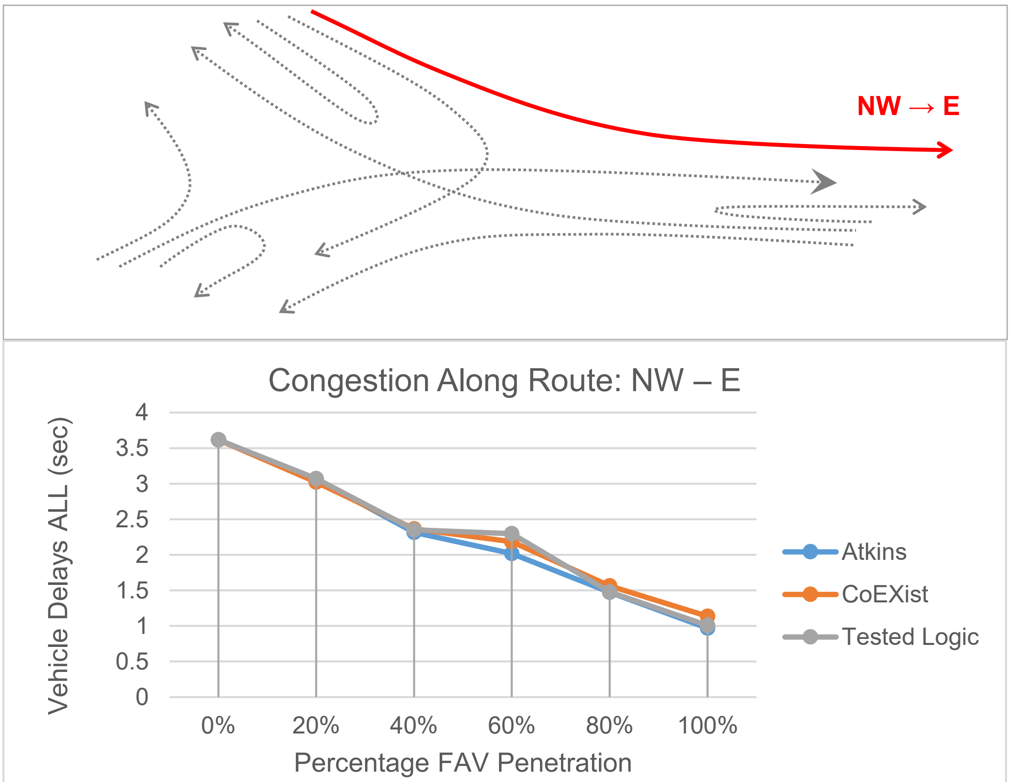


Figure 4-37: Congestion on Route NW - E

The right turn movement on the mainline (46 RFC) to the minor road (0.13 RFC) showed an excellent level of service (LOS) of category A (where delay >10s) when there was 0% ConFAVs in the network. Figure 4-38 shows that LOS improve with the introduction of ConFAVs, as recorded delay decreased.

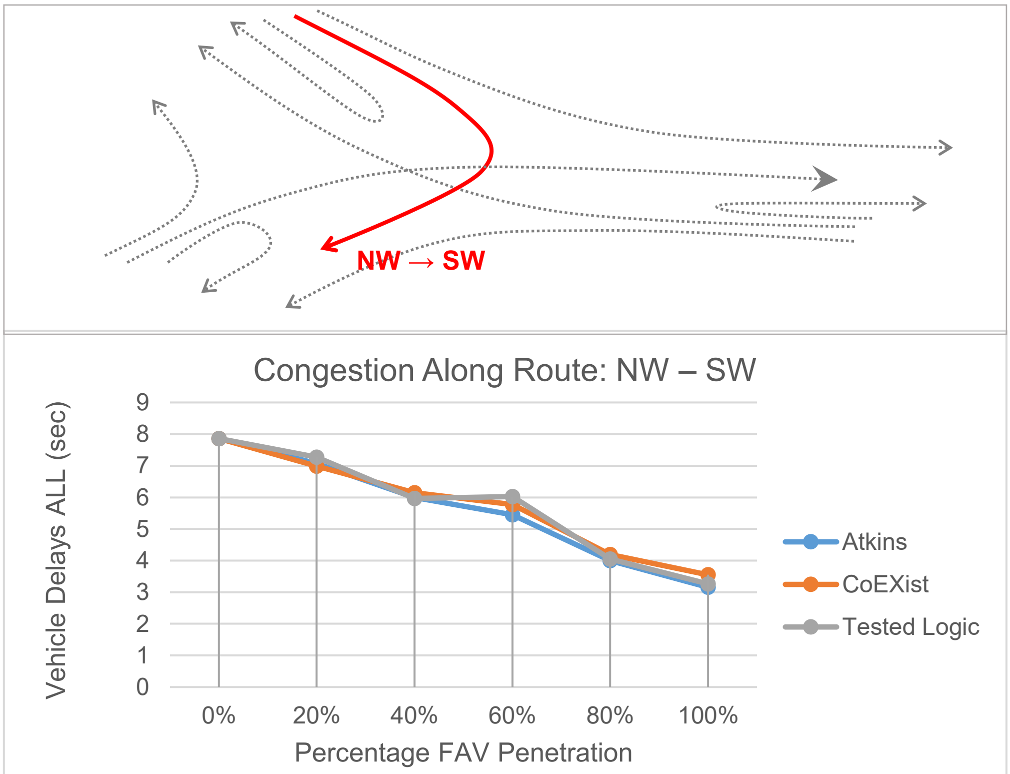
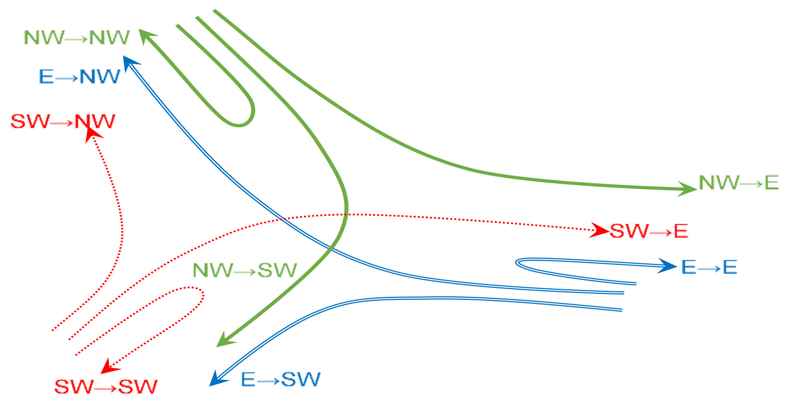


Figure 4-38: Congestion on Route NW - SW

Summary of Results

The congestion along all nine (9) routes identified within this junction type were compared across the 3 ConFAV behavioural models, and the model with the greatest reduction in the total route delay recorded is highlighted in green in Table 4-21 below. The difference between the model with the highest reduction versus the model with the lowest reduction is also shown in the table, with the four greatest differences highlighted in yellow.

Table 4-21 Summary of Changes in congestion for each route at 100% ConFAV penetration



Route	Atkins	CoEXist	Tested Logic	Highest v. Lowest
Route SW - E	-53.58%	-48.48%	-51.20%	**5.10%**
Route SW – SW	-67.27%	-61.80%	-62.59%	**5.47%**
Route SW - NW	-57.74%	-54.98%	-58.81%	3.83%
Route E - E	-49.44%	-49.06%	-49.79%	0.73%
Route E - SW	-85.00%	-84.79%	-84.98%	0.20%
Route E - NW	-88.33%	-87.43%	-88.35%	0.92%
Route NW - E	-73.19%	-68.58%	-72.16%	**4.61%**
Route NW - SW	-59.86%	-54.84%	-58.48%	**5.02%**
Route NW - NW	-51.88%	-53.03%	-54.37%	2.49%

All routes recorded reductions in delay of 48% and higher across all models. ***Atkins however had the greatest reduction in delays on 5 out of 9 routes*** and Tested Logic on the remaining 4 routes. CoEXist was the worst performer for all nine routes, however the differences in performance did not surpass 5.47%. The four greatest differences between the highest performing model and the lowest performing model were as a result of the Atkins behavioural model, two of which were right turns, one U-turn and one through junction movement.

4.3.2 <u>Signal Controlled Junction – Congestion Performance</u>

Each vehicle route decision was plotted to show the total delay (in seconds) experienced at each level of ConFAV penetration. These were classified as the movements shown in Figure 4-39 below, where a total of nine (9) movements were identified.

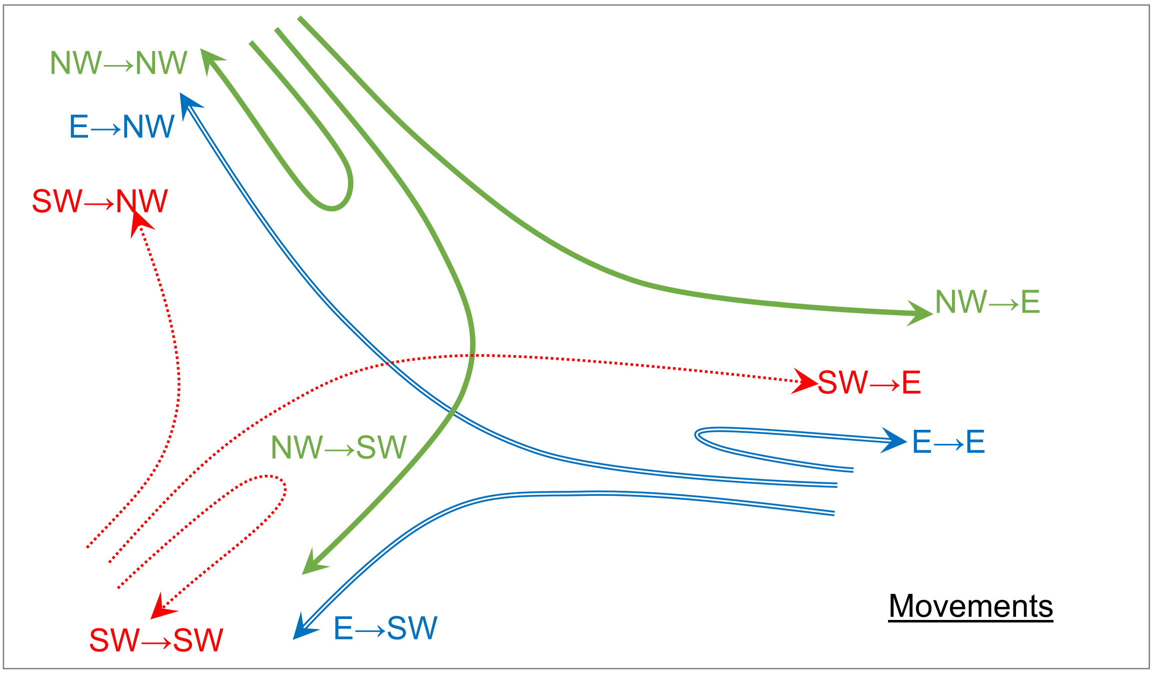


Figure 4-39 Vehicle movements within junction

Results

As previously discussed, the delay of a vehicle on its route choice is calculated by subtracting from its actual travel time a theoretical one in which there were no other vehicles, and/or no signal controls or other reasons for stops to occur (PTV Group, 2018b). Delay due to braking before a PT stop and/or subsequent acceleration after a PT stop was not a factor in the calculation of the delay. Travel time was defined as a measurement parameter so that the software could make this calculation.

The performance of each model for each route are plotted in the graphs shown in Figure 4-40 to Figure 4-48 below. The summary of results is discussed on page 130.

The RFC is the same for all 3 junction types (0.46 for the mainline and 0.13 for the minor road) and the movements are the same across the board.

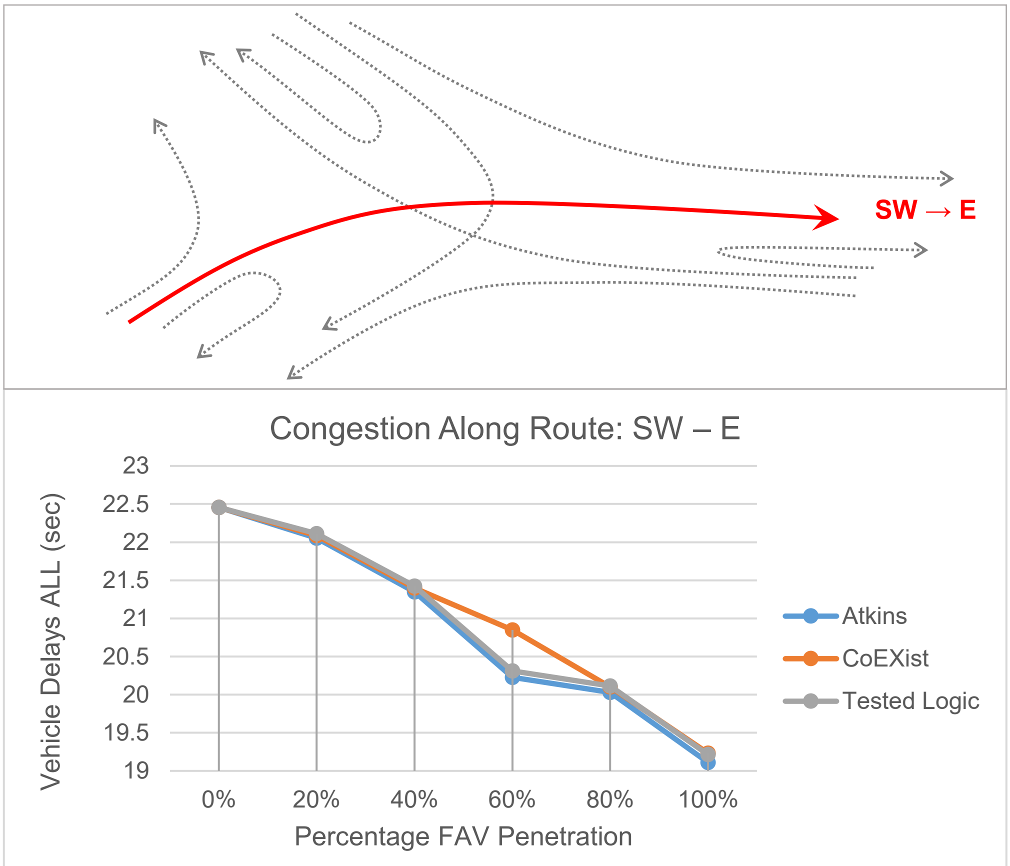


Figure 4-40: Congestion on Route SW – E

The right turn from the minor road to the mainline has seen a drop in level of service from a category C (where delay is >20s to 35s) to a high category B (where delay is >10s to 20s) when all vehicles in the network were ConFAVs. This is shown in Figure 4-40 above.

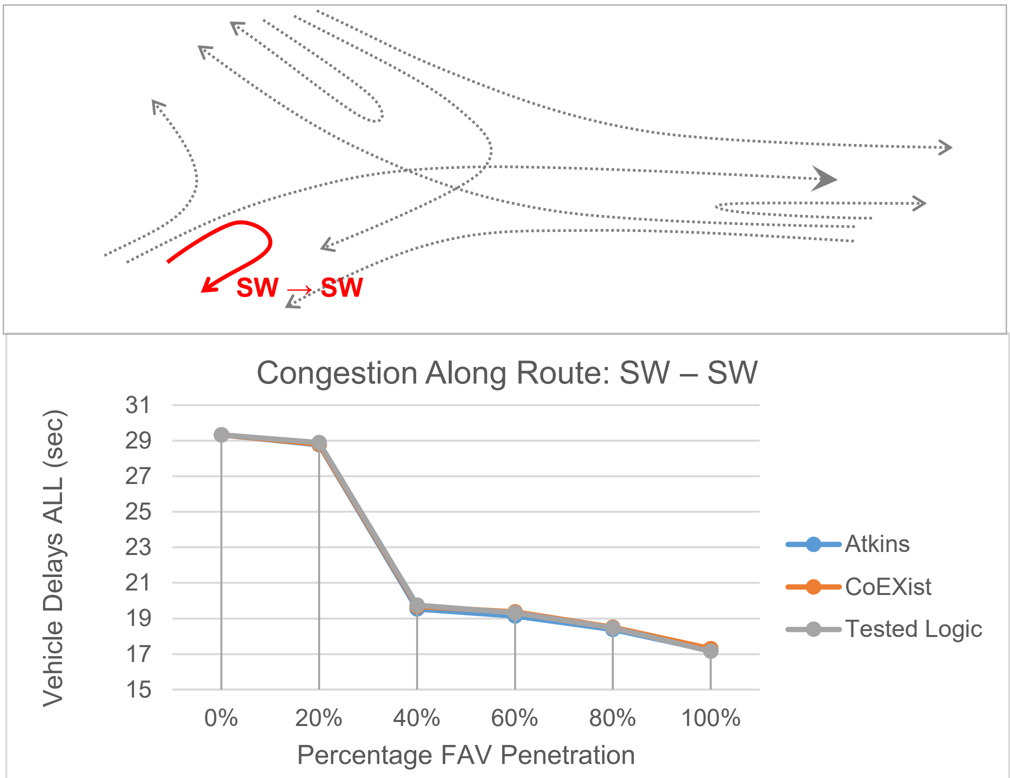


Figure 4-41: Congestion on Route SW – SW

The U-turn within the junction from the minor road to the mainline has seen a drop in level of service from a high category C (where delay is >20s to 35s) to a high category B (where delay is >10s to 20s) when all vehicles in the network were ConFAVs. This is shown in Figure 4-41 above.

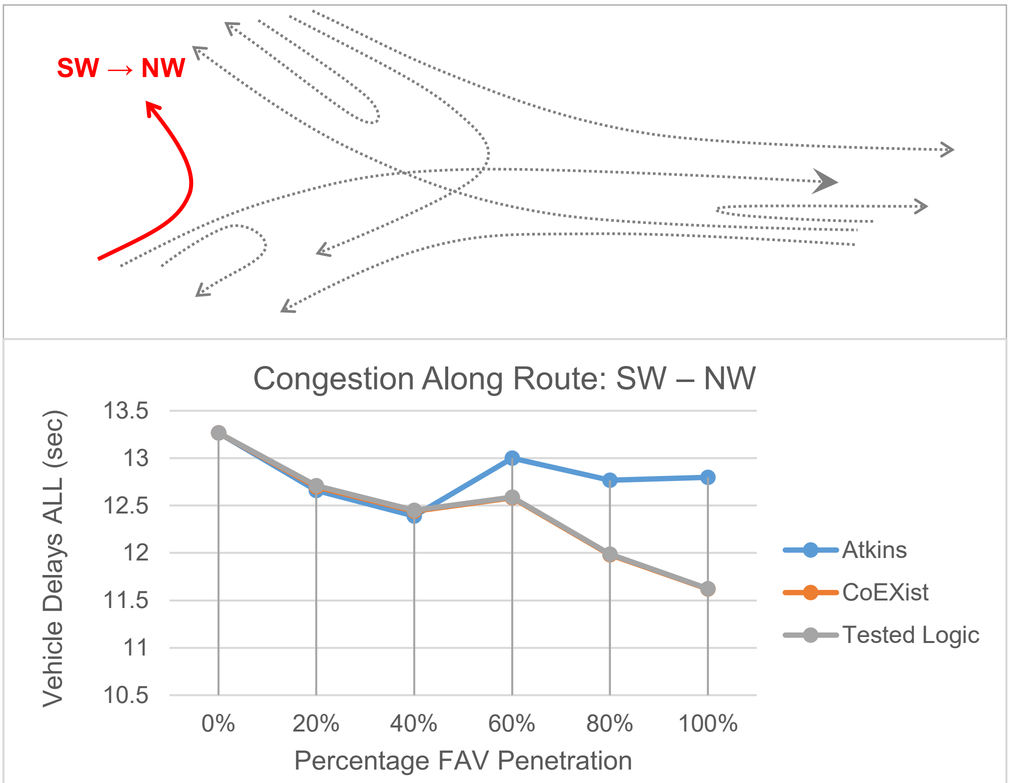


Figure 4-42: Congestion on Route SW – NW

The left turn from the minor road to the mainline has seen a fluctuation in the level of service throughout the introduction of ConFAVs within category B (where delay is >10s to 20s), until it settled on a slightly lower value within category B when all vehicles in the network were ConFAVs. This is shown in Figure 4-42 above.

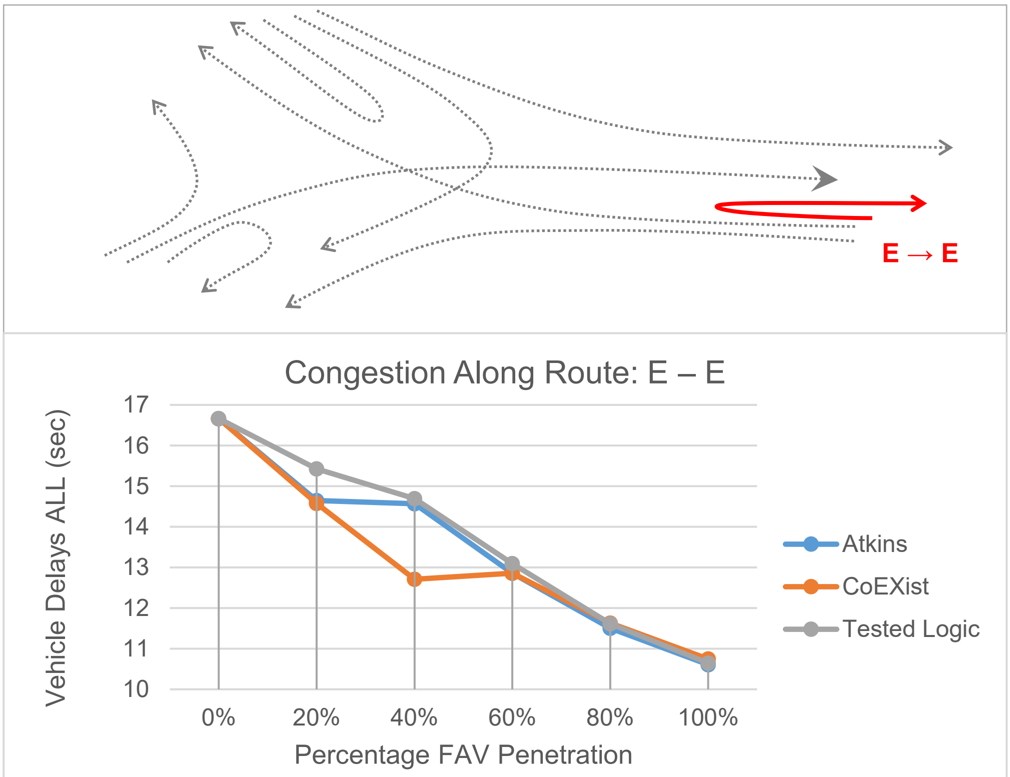


Figure 4-43: Congestion on Route E - E

The U-turn within the junction on the mainline has seen a drop in level of service from a high category B (where delay is >10s to 20s) to a low category B when all vehicles in the network were ConFAVs. This is shown in Figure 4-43 above.

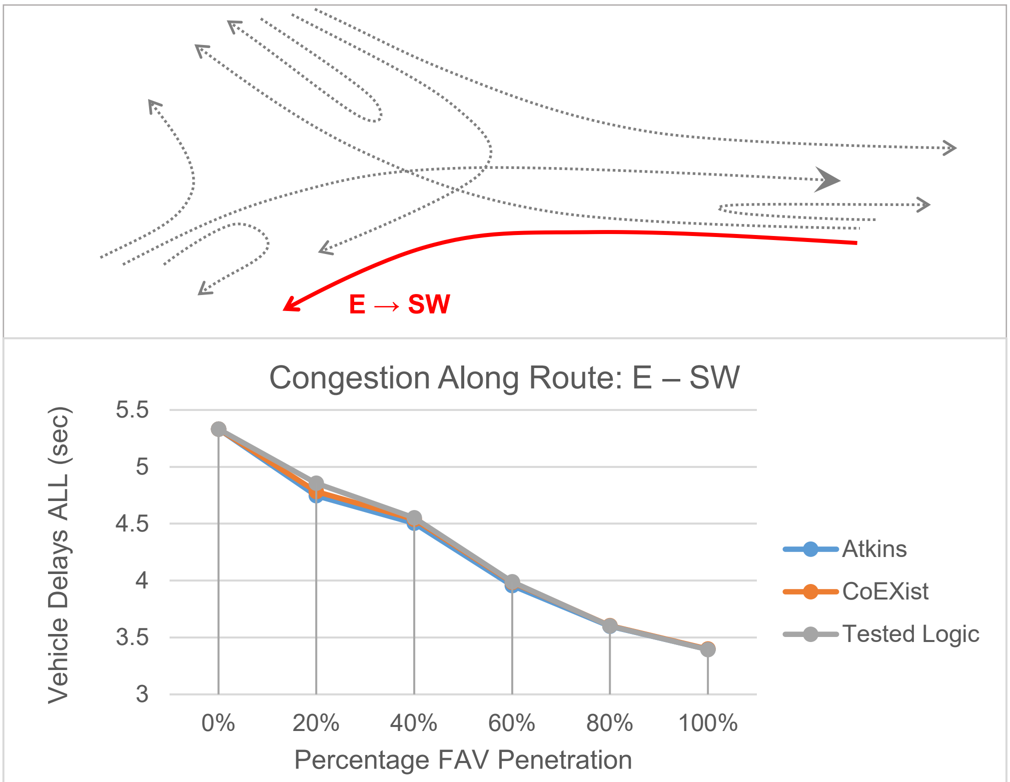


Figure 4-44: Congestion on Route E – SW

The left turn from the mainline into the minor road stayed within LOS category A (where delay is <10s), throughout the experiment, decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-44 above.

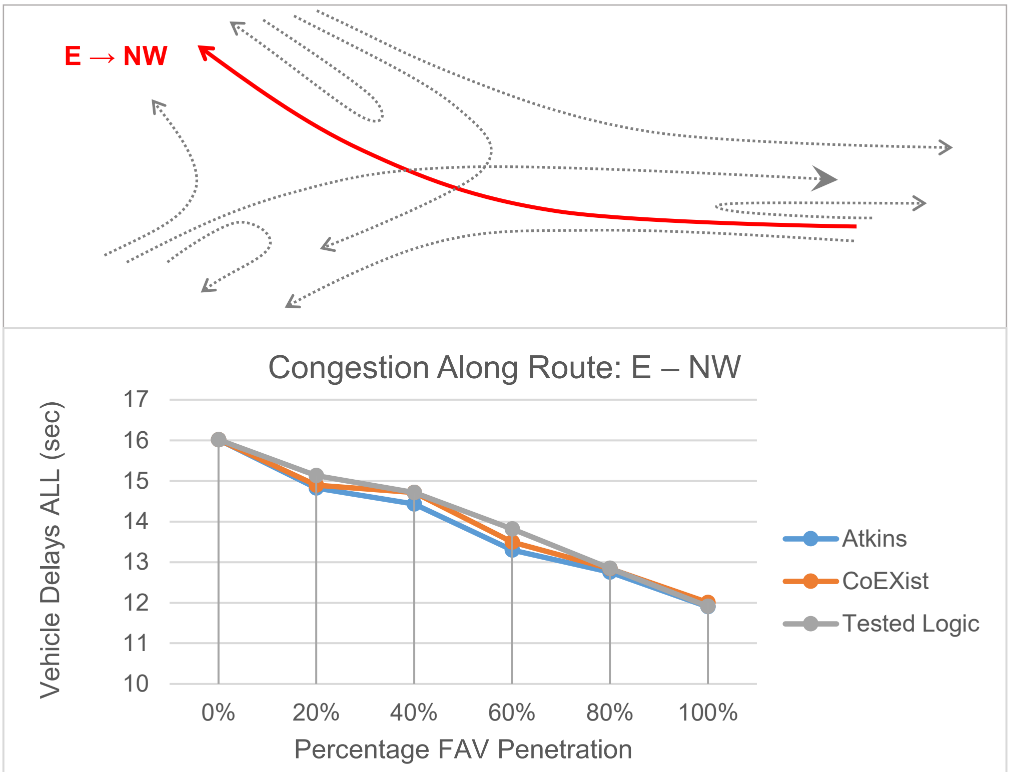


Figure 4-45: Congestion on Route E - NW

Through traffic on the mainline stayed within LOS category B (where delay is >10s to 20s), throughout the experiment, decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-45 above.

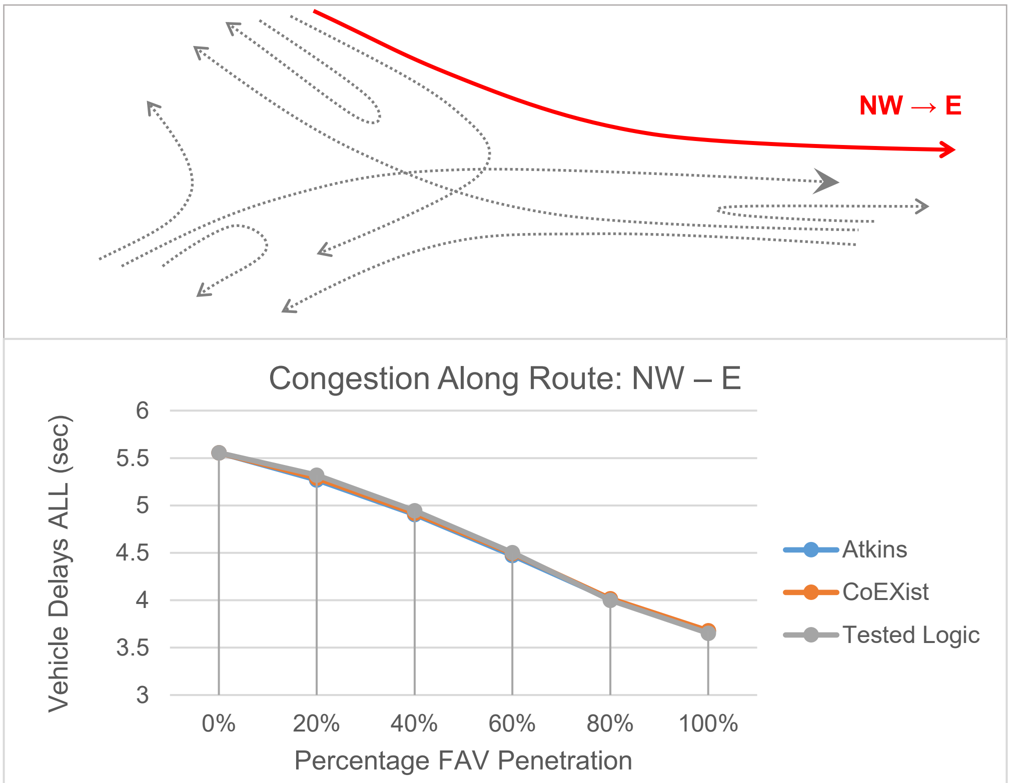


Figure 4-46: Congestion on Route NW - E

Through traffic on the mainline stayed within LOS category A (where delay is <10s), throughout the experiment, decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-46 above.

It should be noted that the previous movement was also on the same mainline, with the same RFC value, but experienced different levels of delays and so were categorised differently.

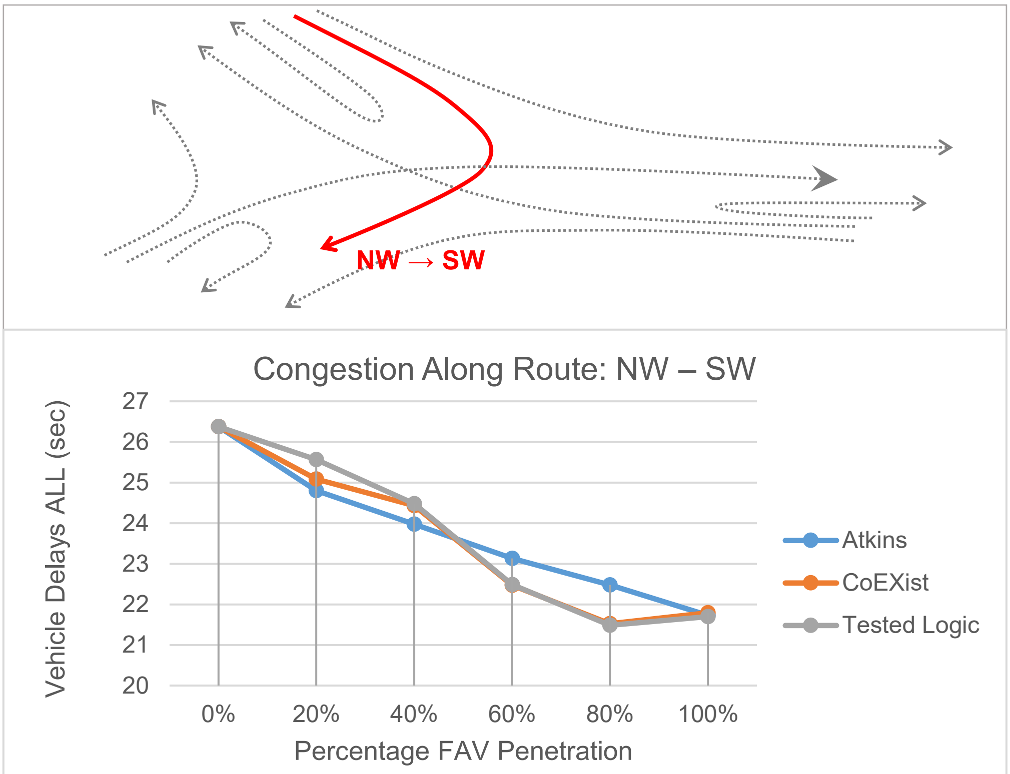


Figure 4-47: Congestion on Route NW – SW

The right turn from the mainline to the minor road stayed within LOS category C (where delay is >20s to 35s), throughout the experiment, decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-47 above.

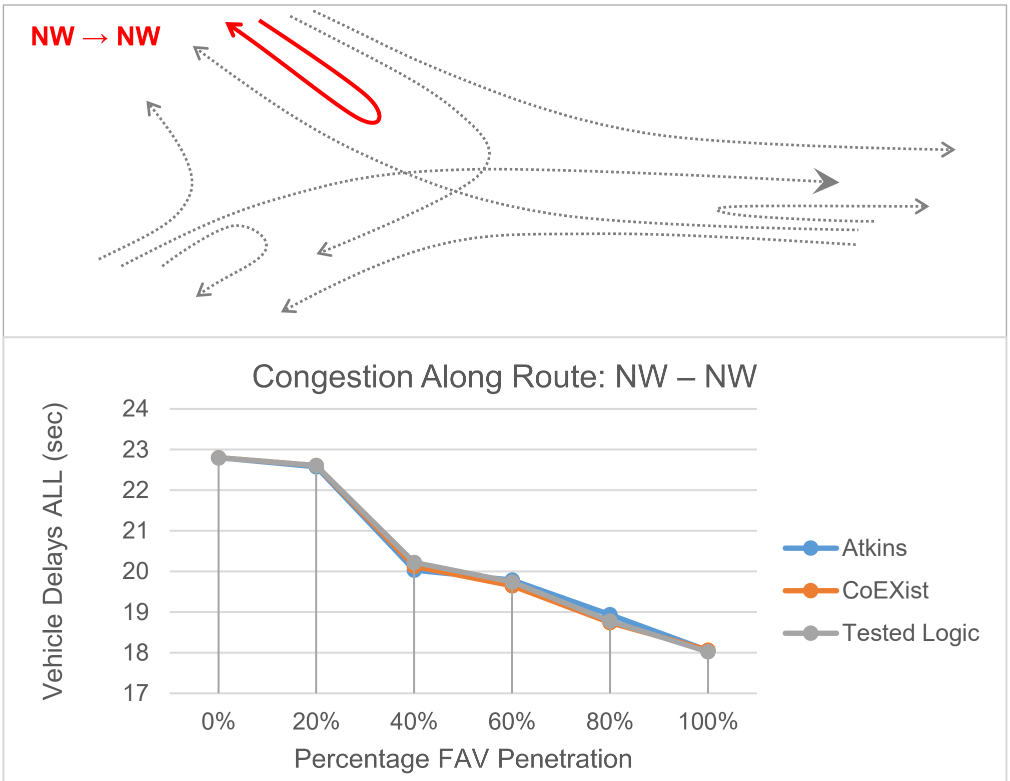


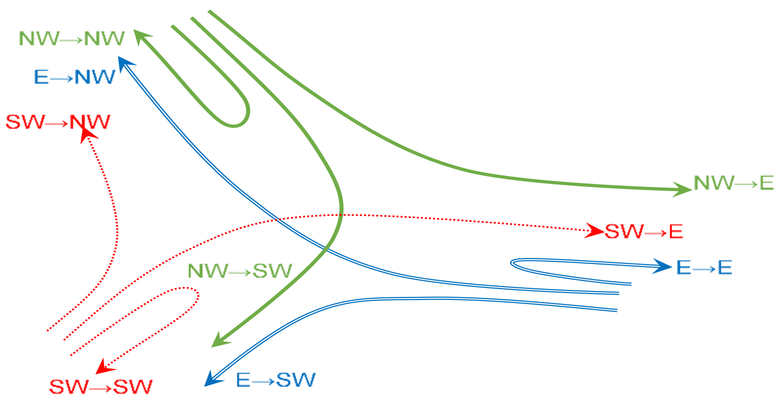
Figure 4-48: Congestion on Route NW - NW

The U-turn on the mainline Dropped from a LOS category C (where delay is >20s to 35s) to a high B (where delay is >10s to 20s), throughout the experiment, decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-48 above.

Summary of Results

The congestion along all nine (9) routes identified within this junction type were compared across the 3 ConFAV behavioural models, and the model with the greatest reduction in the total route delay recorded is highlighted in green in Table 4-22 below. The difference between the model with the highest reduction versus the model with the lowest reduction is also shown in the table, with the four greatest differences highlighted in yellow.

Table 4-22 Summary of Changes in congestion for each route at 100% ConFAV penetration



Route	Atkins	CoEXist	Tested Logic	Highest v. Lowest
Route SW - E	**-14.90%**	-14.35%	-14.44%	**0.54%**
Route SW – SW	-41.40%	-41.00%	**-41.53%**	**0.53%**
Route SW - NW	**-3.53%**	**-12.42%**	**-12.39%**	**8.89%**
Route E - E	**-36.34%**	-35.51%	-36.13%	**0.83%**
Route E - SW	-36.32%	-36.26%	**-36.36%**	0.09%
Route E - NW	**-25.70%**	-25.03%	-25.63%	**0.67%**
Route NW - E	-33.84%	-33.79%	**-34.26%**	0.47%
Route NW - SW	-17.62%	-17.38%	**-17.72%**	0.34%
Route NW - NW	-20.83%	-20.76%	**-20.96%**	0.19%

There was a wide distribution of changes in delay on each route for all models, ranging from -3.53% to -36.34%. Eight out of nine routes showed differences between the highest performing model and the lowest performing model of less than 1 percentage point. There was an irregularity in route SW to NW for the Atkins behavioural model (shown in red in Table 4-22 above), as this movement was the only one to differ greatly from the other 2 models. The data was extracted from the software in the same way for this movement as it was for others, and thus this anomaly cannot be explained by the numbers and could potentially be attributed to the stochastic nature of the model.

Looking at the other movements, ***Tested logic was the best performer with 5 movements having the least amount of congestion at 100% ConFAV penetration***. However, due to the difference between the best and worst performing models being less than a percentage point, the impact of the parameters of this behaviour model is potentially insignificant.

There were no patterns observed for junction movement types (right turn, left turn or through junction movement) and of the 8 movements considered above, the three routes that the Atkins behavioural model resulted in the greatest reduction of congestion (when compared with the other two models) showed the top 3 greatest difference from the worst performing model.

junction movement.

4.3.3 Roundabout – Congestion Performance

Each vehicle route decision was plotted to show the total delay (in seconds) experienced at each level of ConFAV penetration. These were classified as the movements shown in Figure 4-49 below, where a total of nine (9) movements were identified.

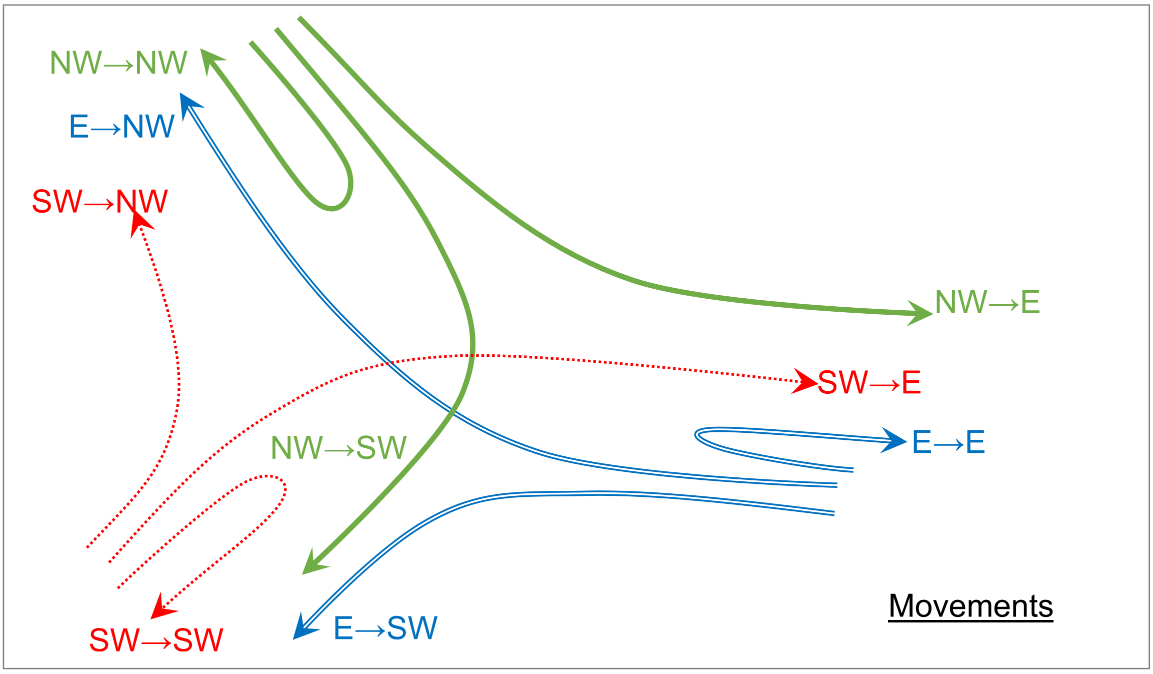


Figure 4-49 Vehicle movements within junction

Results

As previously discussed, the delay of a vehicle on its route choice is calculated by subtracting from its actual travel time a theoretical one in which there were no other vehicles, and/or no signal controls or other reasons for stops to occur (PTV Group, 2018b). Delay due to braking before a PT stop and/or subsequent acceleration after a PT stop was not a factor in the calculation of the delay. Travel time was defined as a measurement parameter so that the software could make this calculation.

The performance of each model for each route are plotted in the graphs shown in Figure 4-50 to Figure 4-58 below. The summary of results is discussed on page 141.

The RFC is the same for all 3 junction types (0.46 for the mainline and 0.13 for the minor road) and the movements are the same across the board.

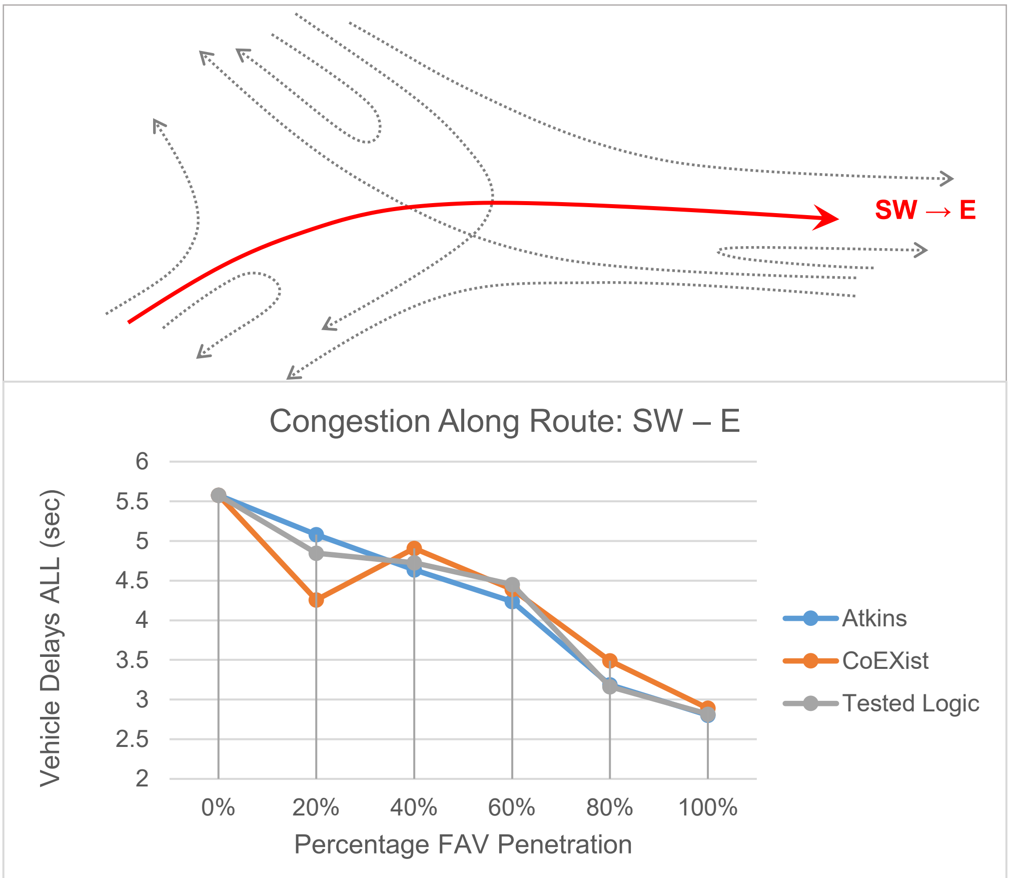


Figure 4-50: Congestion on Route SW - E

The right turn from the minor road onto the mainline remained within LOS category A (where delay is <10s) throughout the experiment decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-48Figure 4-50 above.

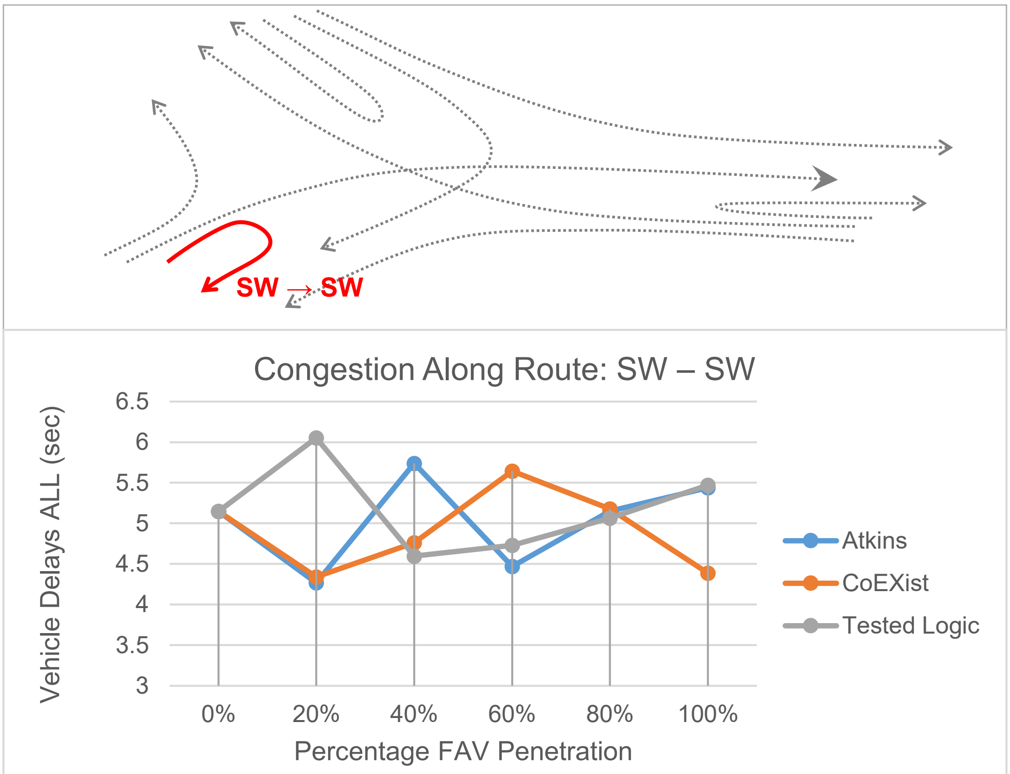


Figure 4-51: Congestion on Route SW – SW

The U-turn on the minor road produced inconsistent results that showed no patterns but managed to remain within LOS category A (where delay is <10s) throughout the experiment. This is shown in Figure 4-48Figure 4-51 above.

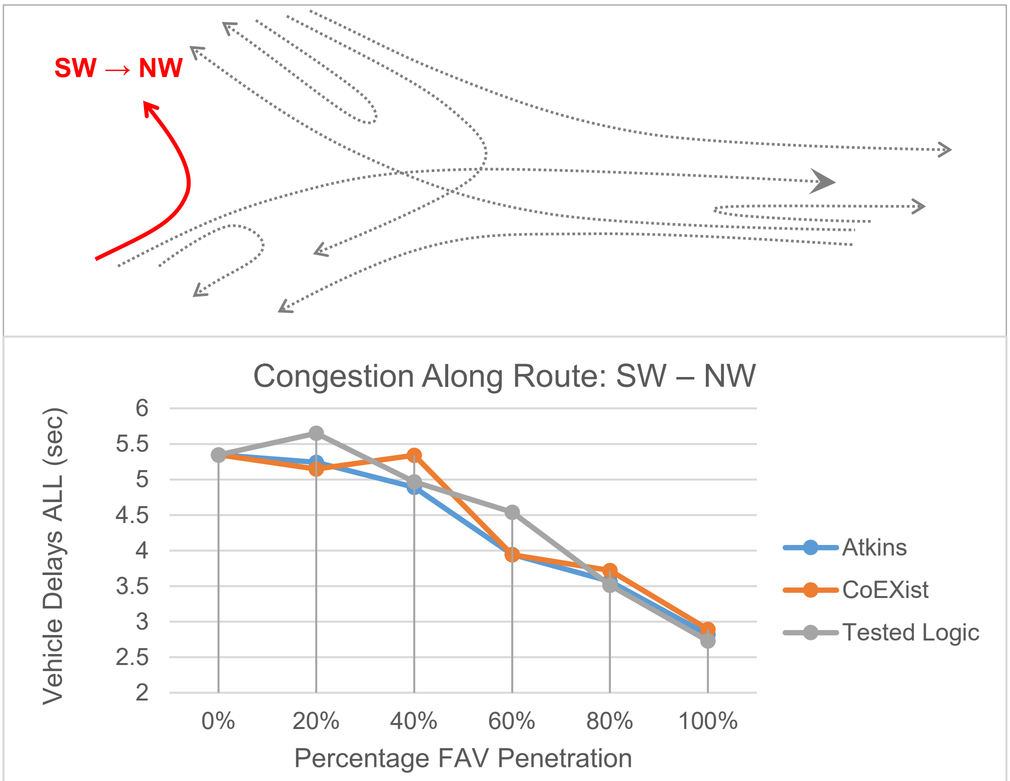


Figure 4-52: Congestion on Route SW - NW

The left turn from the minor road onto the mainline remained within LOS category A (where delay is <10s) throughout the experiment decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-48Figure 4-52 above.

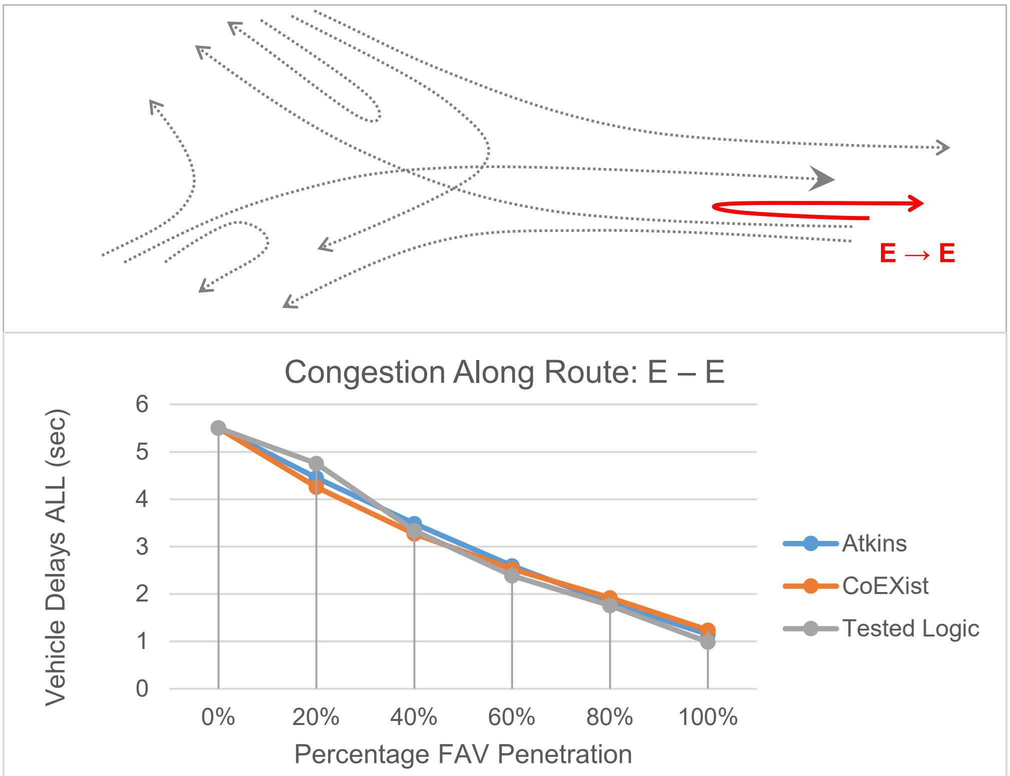


Figure 4-53: Congestion on Route E - E

The U-turn on the Eastern side of the mainline remained within LOS category A (where delay is <10s) throughout the experiment decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-48Figure 4-53 above.

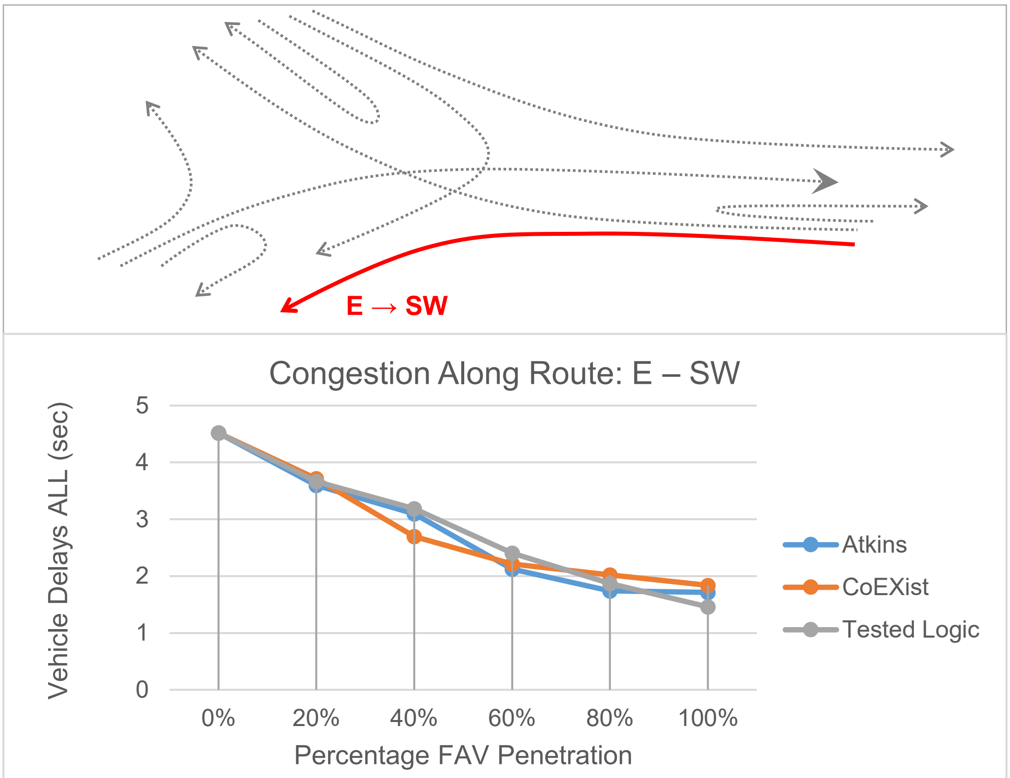


Figure 4-54: Congestion on Route E - SW

The left turn from the Eastern side of the mainline remained within LOS category A (where delay is <10s) throughout the experiment decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-48Figure 4-54 above.

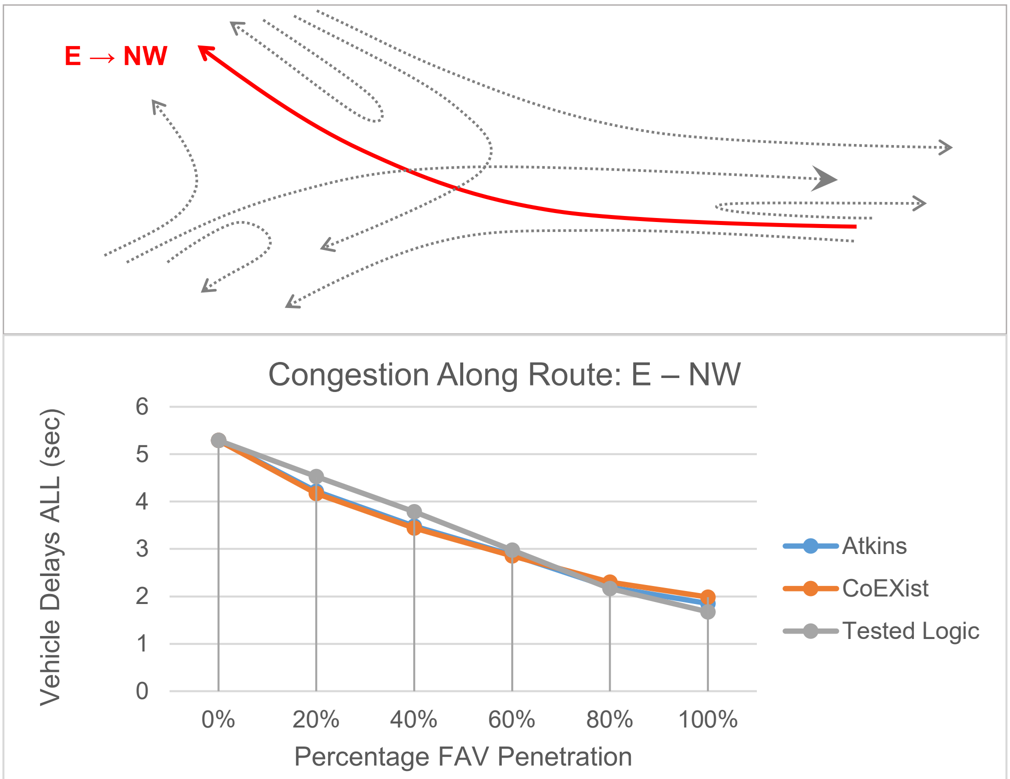


Figure 4-55: Congestion on Route E - NW

Northwest bound traffic from the Eastern side of the mainline remained within LOS category A (where delay is <10s) throughout the experiment decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-48Figure 4-55 above.

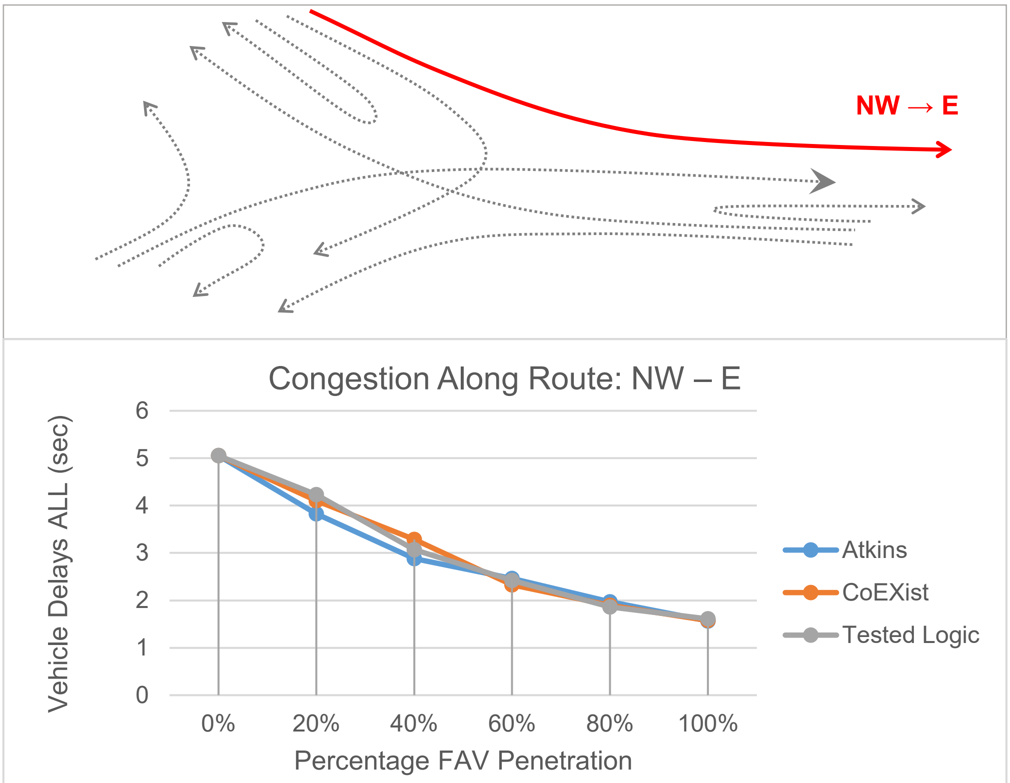


Figure 4-56: Congestion on Route NW - E

Eastbound bound traffic from the north western side of the mainline remained within LOS category A (where delay is <10s) throughout the experiment decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-48Figure 4-56 above.

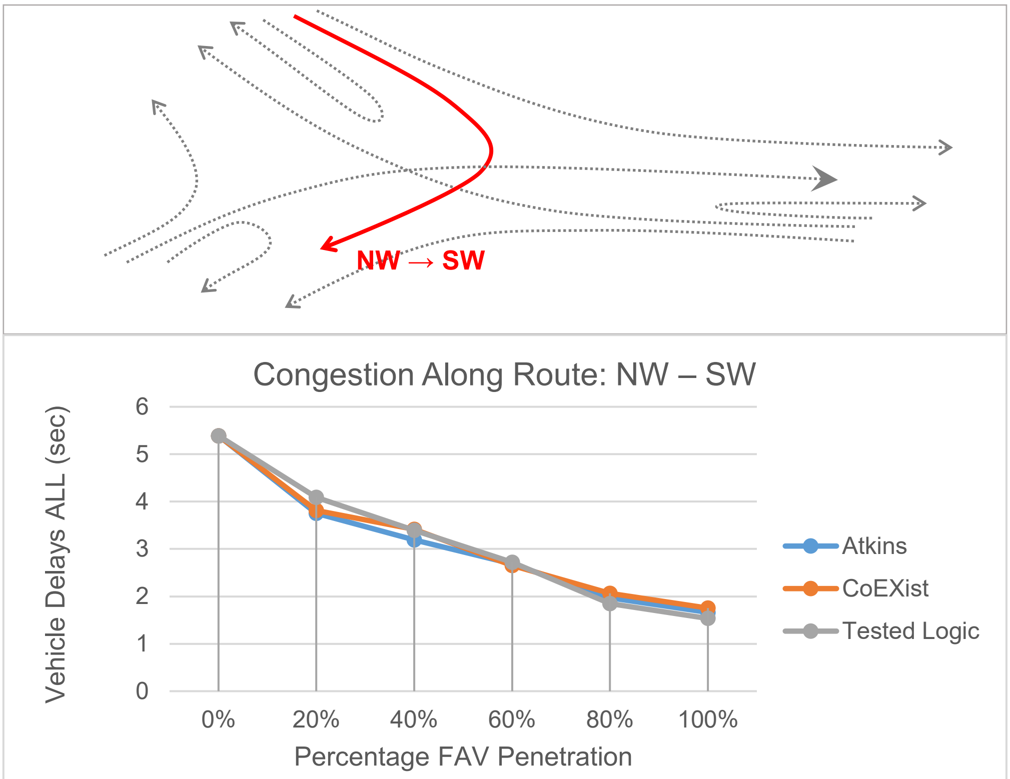


Figure 4-57: Congestion on Route NW - SW

Traffic turning right, onto the minor road from the mainline remained within LOS category A (where delay is <10s) throughout the experiment decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-48Figure 4-57 above.

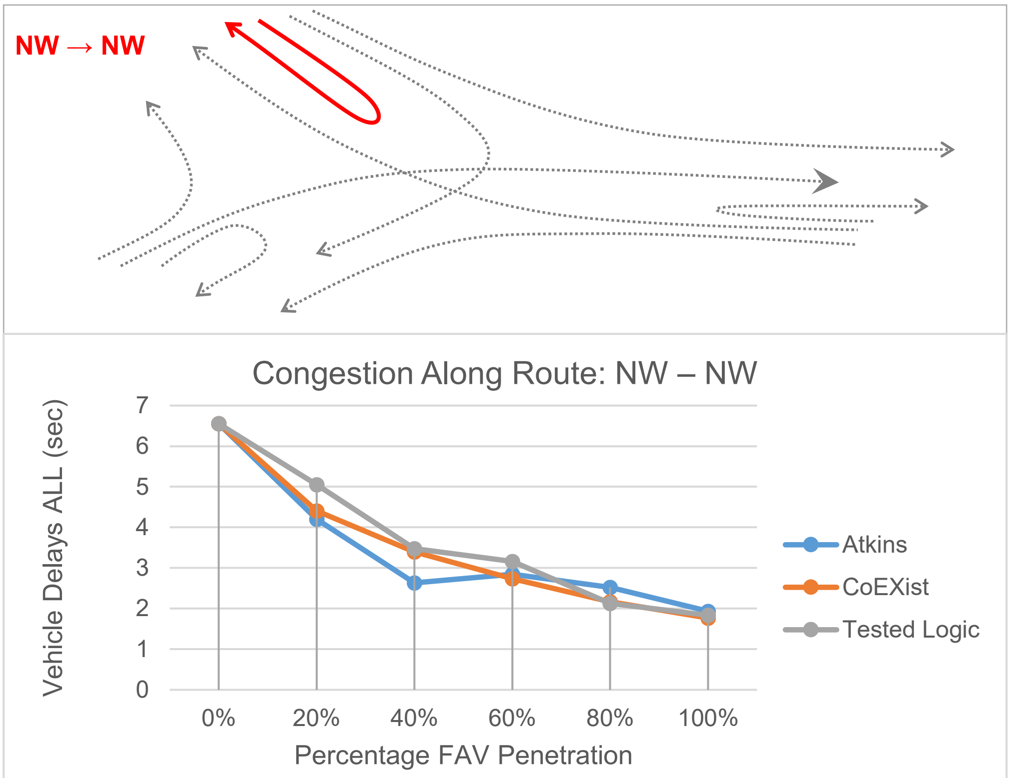


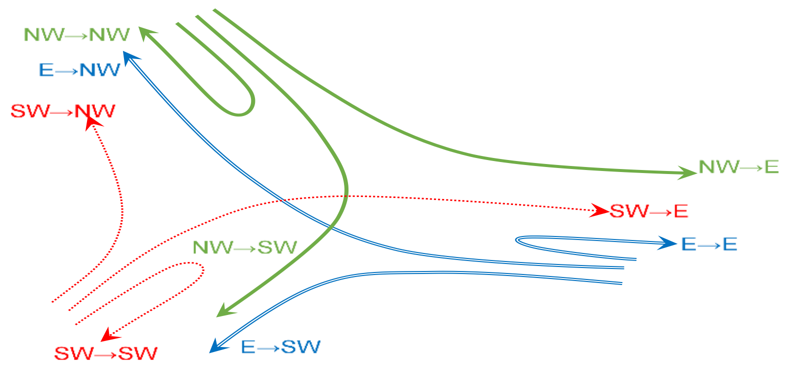
Figure 4-58: Congestion on Route NW - NW

Traffic making a U-turn on the north western side of the mainline remained within LOS category A (where delay is <10s) throughout the experiment decreasing in delay with the increase in the number of ConFAVs withing the network. This is shown in Figure 4-48Figure 4-58 above.

__Summary of Results__

The congestion along all nine (9) routes identified within this junction type were compared across the 3 ConFAV behavioural models, and the model with the greatest reduction in the total route delay recorded is highlighted in green in Table 4-23 below. The difference between the model with the highest reduction versus the model with the lowest reduction is also shown in the table, with the four greatest differences highlighted in yellow.

Table 4-23 Summary of Changes in congestion for each route at 100% ConFAV penetration



Route	Atkins	CoEXist	Tested Logic	Highest v. Lowest
Route SW - E	**-49.73%**	-48.18%	-49.49%	1.56%
Route SW – SW	**5.65%**	**-14.81%**	**6.23%**	**21.04%**
Route SW - NW	-47.29%	-45.89%	**-48.96%**	3.06%
Route E - E	-79.11%	-77.48%	**-82.11%**	**4.63%**
Route E - SW	-62.06%	-59.33%	**-67.70%**	**8.37%**
Route E - NW	-65.01%	-62.45%	**-68.35%**	**5.90%**
Route NW - E	**-68.99%**	-68.83%	-68.15%	0.84%
Route NW - SW	-69.15%	-67.47%	**-71.52%**	**4.05%**
Route NW - NW	-70.46%	**-73.01%**	-72.01%	2.55%

The simulations recorded a wide distribution of changes in delay on each route for all models ranging from an increase in delay by **6.23%** to a reduction in delay of **-73.01%**. There was an irregularity in route SW to SW for all three behavioural models (shown in red in Table 4-23 above), as this movement was the only one to fluctuate greatly with each level of penetration (as seen in Table 4-23 above). The data was extracted from the software in the same way for this movement as it was for others, and thus this anomaly cannot be explained by the numbers. As there was no clear pattern for any of the three models along this route, it is impossible to tell if this could potentially be attributed to the stochastic behaviour of the model.

Looking at the other eight (8) movements, ***Tested logic was the best performer with 5 movements having the least number of delays at 100% ConFAV penetration***. The top four movements that showed the highest difference between the best and worst performing models were as a result of the Tested Logic behavioural model. There were no patterns observed for junction movement types (right turn, left turn or through junction movement) and of the 8 movements considered above.

4.3.4 <u>Safety Performance of Behavioural Models</u>

A Surrogate Safety Assessment was carried out, as described in section 3.6 of chapter 3, to compare the safety performance of each driving behaviour model by analysing potential conflicts of the vehicle trajectories exported from the simulation.

Using the Conflict Speed VS Time to Accident graph shown in Figure 3-30 of chapter 3, the time to collision (TTC) parameters used for the assessment were 2.0 for serious conflicts and 3.0 non-serious conflicts and the results for each junction type are shown in the sections below.

<u>Priority Junction</u>

The results from the surrogate safety assessment carried out within the priority junction are plotted on the graph in Figure 4-57 below.

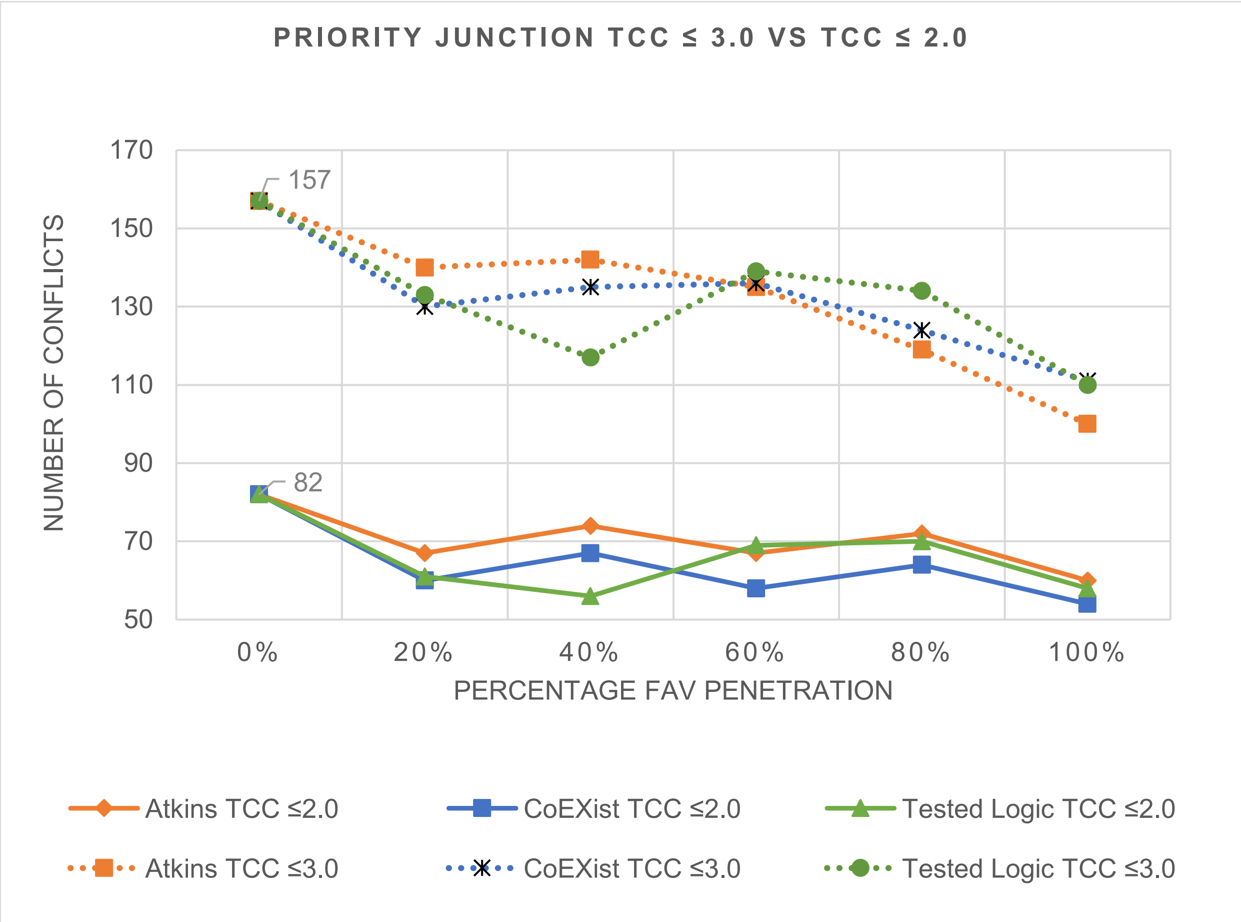


Figure 4-59: Serious VS Non-Serious Conflicts within the Priority Junction

Taking a closer look at the results in Figure 4-57 above, we can see number of vehicular conflicts trending downwards when there is a 100% penetration of ConFAVs. This is plotted in the graph shown in Figure 4-58 below.

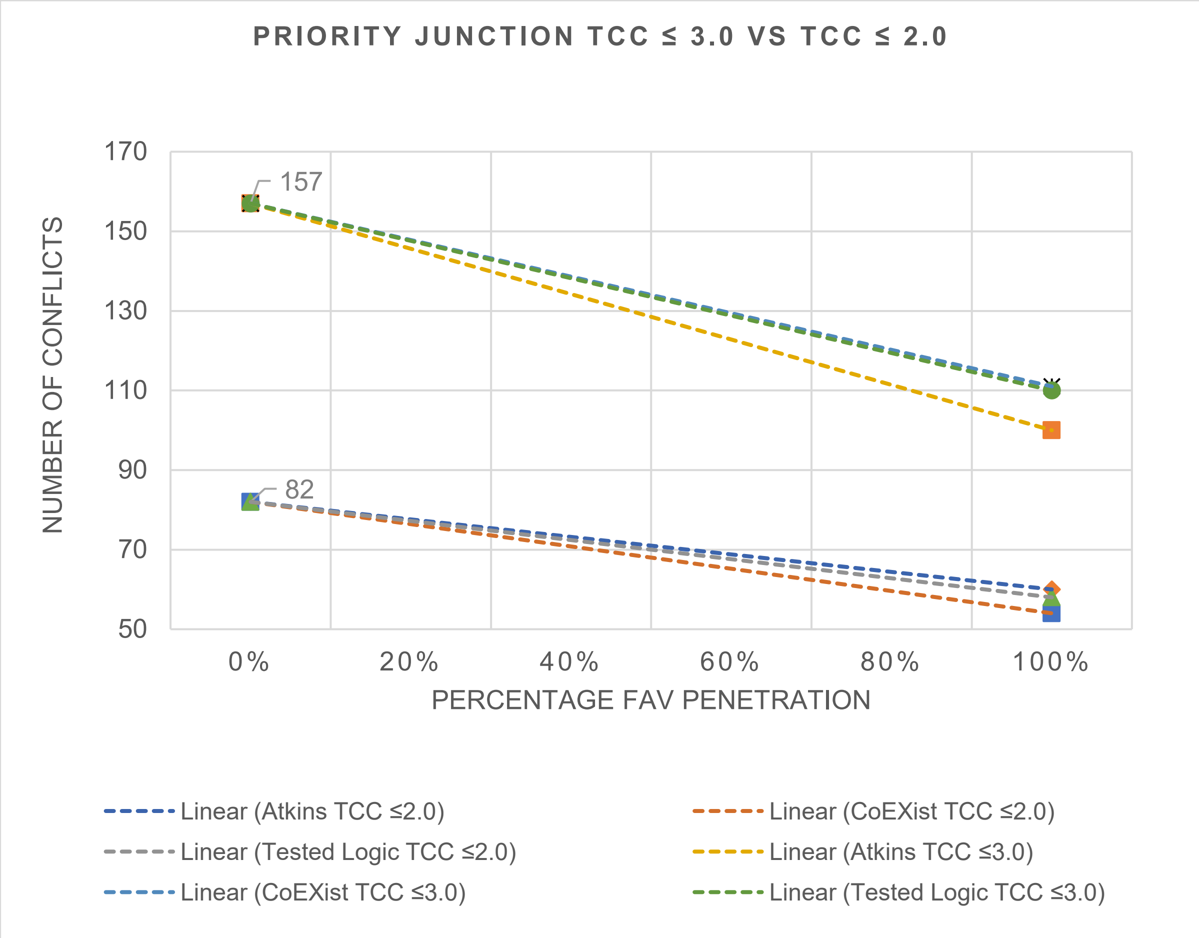


Figure 4-60: Serious VS Non-Serious Conflicts within the Priority Junction

For serious conflicts (TTC≤2.0), the results were quite close with only a 7.32 percentage difference between the worst performing and the best performing model. CoEXist showed the least number of potentially serious conflicts within the junction with a reduction of 34.15% at 100% ConFAV penetration.

For non-serious conflicts (TTC≤3.0), the results were again quite close with only a 7.01 percentage difference between the worst performing and the best performing model. Atkins showed the least number of potential conflicts within the junction with a reduction of 36.31% at 100% ConFAV penetration.

Table 4-24 Changes in Number of Conflicts within the Priority Junction

ConFAV Penetration	Atkins	CoEXist	Tested Logic
Serious Conflicts TTC≤2.0			
0%	82	82	82
100%	60	**54**	58
Percentage Change	-26.83%	**-34.15%**	-29.27%
Non-Serious Conflicts TTC≤3.0			
0%	157	157	157
100%	**100**	111	110
Percentage Change	**-36.31%**	-29.30%	-29.94%

Signal-Controlled Junction

The results from the surrogate safety assessment carried out within the signal-controlled junction are plotted on the graph in Figure 4-61 below.

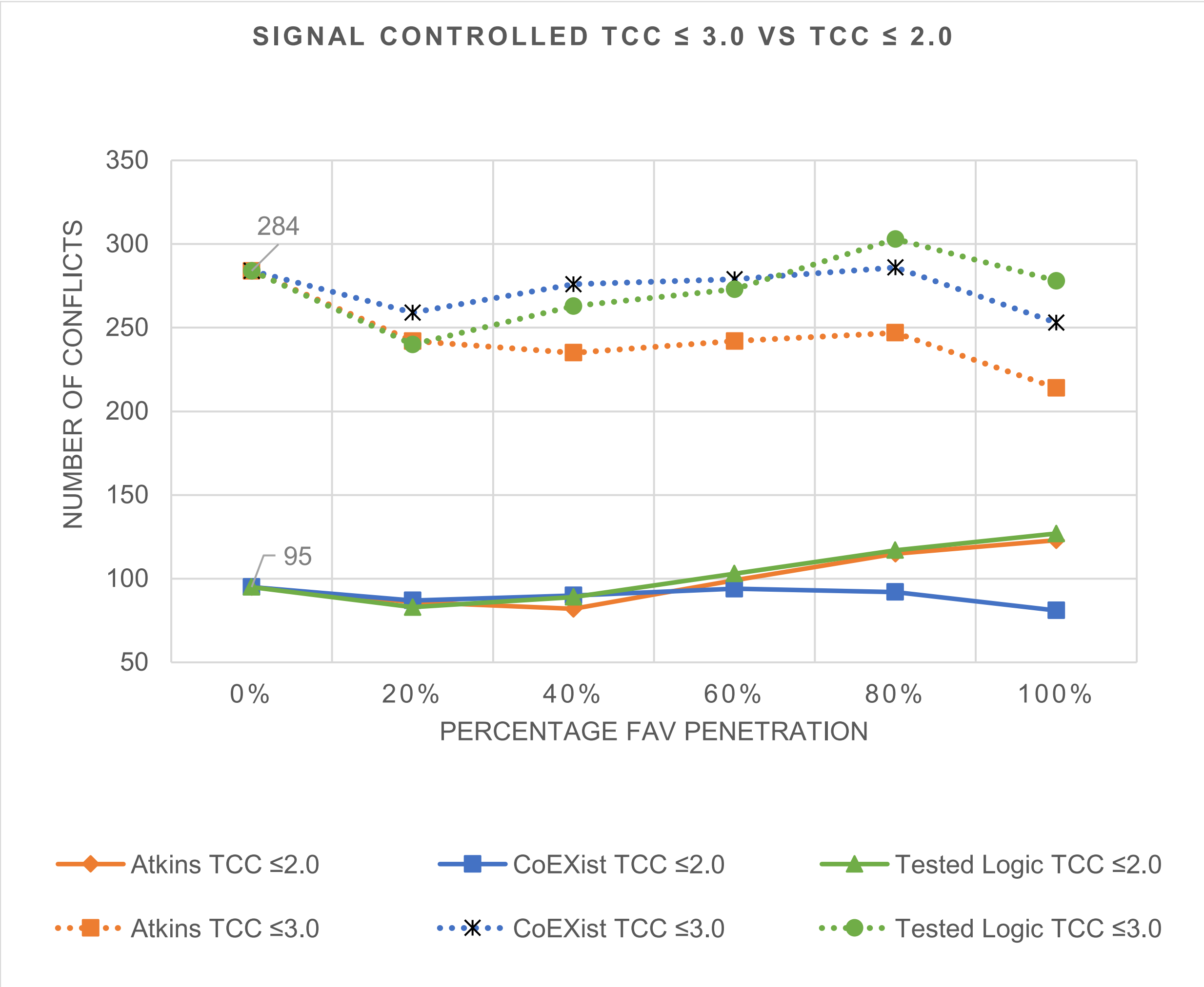


Figure 4-61: Serious VS Non-Serious Conflicts within the Signal-Controlled Junction

The graph illustrates that the number of non-serious vehicular conflicts for each model was gently trending downwards when there is a 100% penetration of ConFAVs, while serious conflicts increased slightly for Atkins and Tested Logic. The trendline for each model is plotted in the graph shown in Figure 4-62 below showing the non-serious conflicts (TTC≤3.0) on top and serious conflicts (TTC≤2.0) on the bottom.

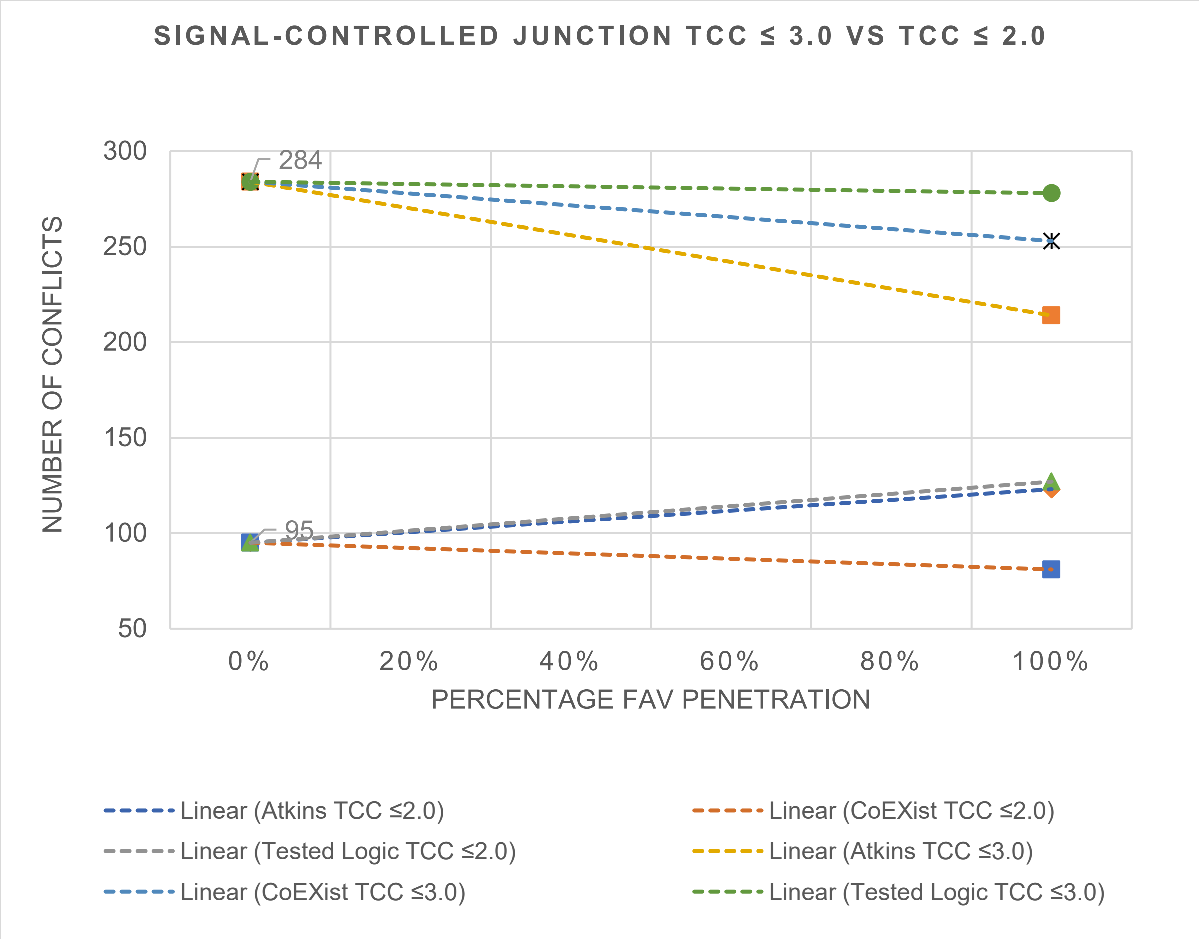


Figure 4-62: Serious VS Non-Serious Conflicts within the Signal-Controlled Junction

When plotting the serious conflicts recorded in the signal-controlled junction, the results were quite opposite to the trends in the priority junction. At 100% ConFAV penetration both the Atkins and Tested Logic models recorded increases of 29.47% and 33.68% respectively, while CoEXist showed a reduction of 14.74%.

For non-serious conflicts, the results from each model were trending downwards with a 22.54 percentage difference between the worst performing and the best performing model. At 100% ConFAV penetration, Atkins showed the least number of potential conflicts within the junction with a reduction of 24.65%.

Table 4-25 Changes in Number of Conflicts within the Signal-Controlled Junction

ConFAV Penetration	Atkins	CoEXist	Tested Logic
Serious Conflicts TTC≤2.0			
0%	95	95	95
100%	123	**81**	127
Percentage Change	**+29.47%**	**-14.74%**	**+33.68%**
Non-Serious Conflicts TTC≤3.0			
0%	284	284	284
100%	**214**	253	278
Percentage Change	**-24.65%**	-10.92%	-2.11%

Roundabout

The results from the surrogate safety assessment carried out within the roundabout are plotted on the graph in Figure 4-63 below.

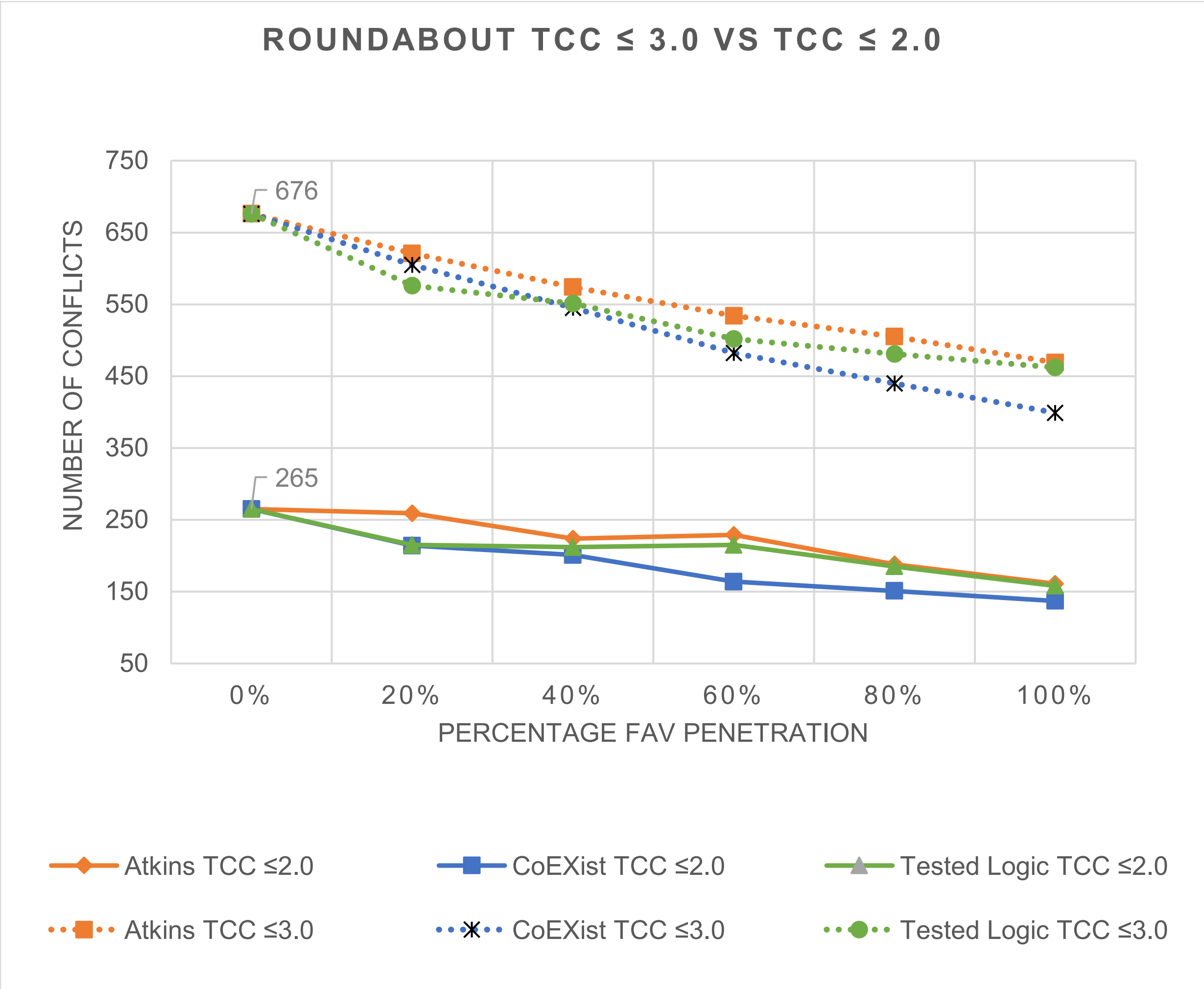


Figure 4-63: Serious VS Non-Serious Conflicts within the Roundabout

The graph illustrates that both non-serious conflicts (TTC≤3.0) and serious conflicts (TTC≤2.0) for all models were trending downwards when there is a 100% penetration of ConFAVs. The trendline for each model is plotted in the graph shown in Figure 4-64 below showing the non-serious conflicts (TTC≤3.0) on top and serious conflicts (TTC≤2.0) on the bottom.

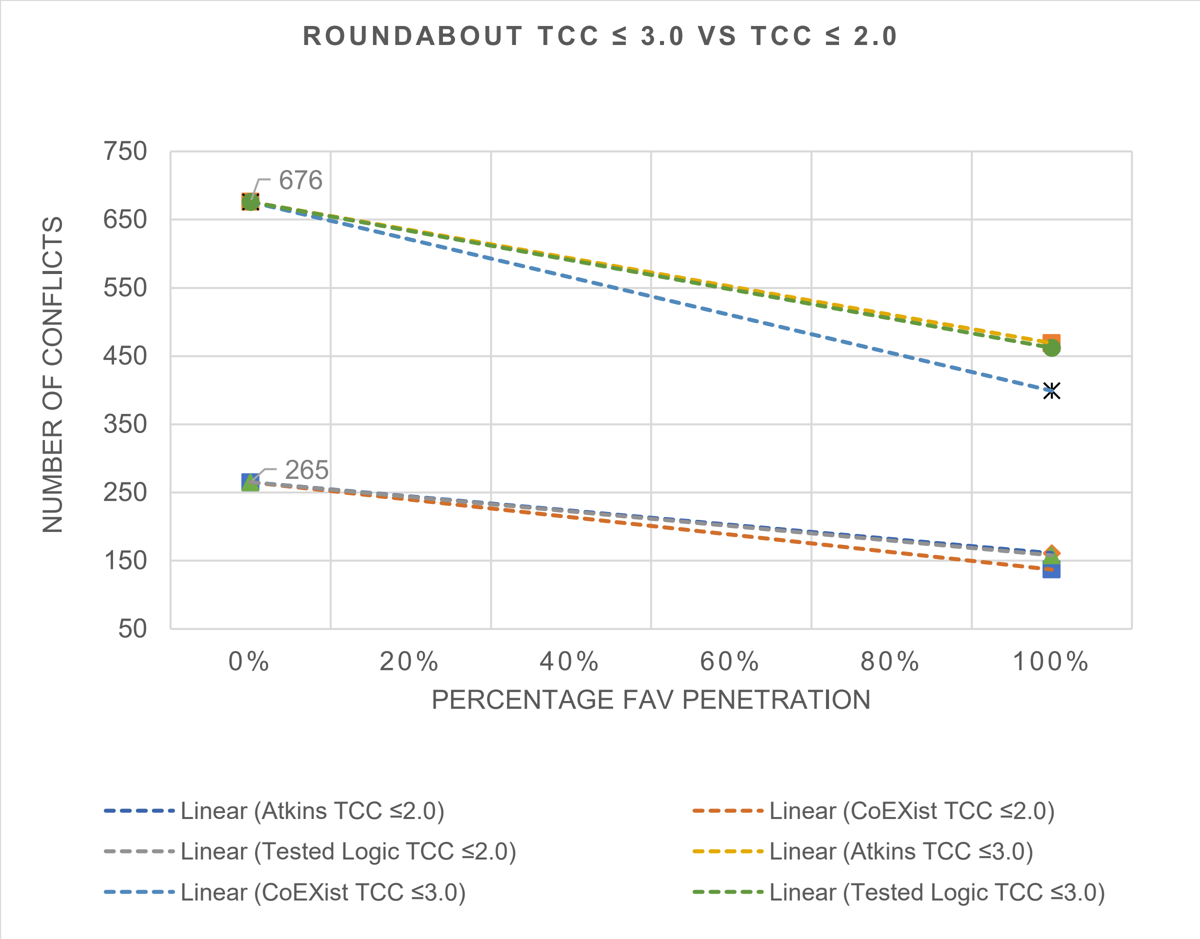


Figure 4-64: Serious VS Non-Serious Conflicts within the Roundabout

Serious conflicts showed a marked reduction at 100% ConFAV penetration with the CoEXist model recording a 48.30% reduction in potentially serious conflicts. Overall, there was a 9.05 percentage difference between the best and the worst performing model.

For non-serious conflicts, while the roundabout recorded 676 non serious conflicts with 0% ConFAVs present, at a 100% ConFAV penetration rate the results from each model were trending downwards with a 10.36 percentage difference between the worst performing and the best performing model. At 100% ConFAV penetration, CoEXist showed the least number of potential conflicts within the junction with a reduction of 40.98%.

Table 4-26 Changes in Number of Conflicts within the Roundabout

ConFAV Penetration	Atkins	CoEXist	Tested Logic
Serious Conflicts TTC≤2.0			
0%	265	265	265
100%	161	**137**	158
Percentage Change	-39.25%	**-48.30%**	-40.38%
Non-Serious Conflicts TTC≤3.0			
0%	676	676	676
100%	469	**399**	462
Percentage Change	-30.62%	**-40.98%**	-31.66%

Results Summary

The CoEXist behavioural model consistently demonstrated a reduction in the number of serious conflicts (TTC≤2.0) at 100% ConFAV network penetration. It recorded a 34.15% reduction within priority junctions, 14.74% reduction within signal-controlled junctions, and 48.30% reduction within roundabouts. While the Atkins and Tested Logic behaviour models showed a decrease in both priority junctions and roundabouts, they displayed a significant increase within signal-controlled junctions ranging between a 29.47% to 33.68% increase.

All models consistently showed a reduction in the number of non-serious conflicts (TTC≤3.0) recorded, with the roundabout recording the highest percentage reductions. Atkins had the best performance in the priority junction by recording a 36.31% reduction and also within the signal-controlled junction with a reduction of 24.65%. CoEXist performed the best within the roundabout by recording a 40.98% reduction.

4.4 Conclusion and Recommendation

As shown in Table 4-27 below, all three models recorded a reduction in delays within the junction, ranging from an average of -28.01% to -66.04%. The CoEXist model was the worst performer among the three, with a difference of 0.37 to 3.21 percentage points when compared with the best performing model.

However, when comparing the safety performance of all models, CoEXist was the only one to consistently reduce the total number of serious conflicts. The CoEXist model was the best performer, with a difference of 7.32 to 48.42 percentage points when compared with the worst performing models.

Table 4-27 Changes in Number of Conflicts within the Roundabout

Change in Average Delays				
	Atkins	**CoEXist**	**Tested Logic**	**Best vs Worst**
Priority	**-65.14%**	-62.56%	-64.53%	2.59%
Signal-controlled	-28.37%	-28.01%	**-28.38%**	0.37%
Roundabout	-63.97%	-62.83%	**-66.04%**	3.21%
Change in the Number of Serious Conflicts Recorded				
	Atkins	**CoEXist**	**Tested Logic**	**Best vs Worst**
Priority	-26.83%	**-34.15%**	-29.27%	7.32%
Signal-controlled	29.47%	**-14.74%**	33.68%	48.42%
Roundabout	-39.25%	**-48.30%**	-40.38%	9.05%

4.4.1 Recommendation

As the difference between CoEXist and best performing models for average delays is only up to a maximum of **3.21** percentage points, while the difference between CoEXist and the worst performing models for serious conflicts ranges between **7.32** and **48.42** percentage points, it can be said that benefit of a reduction in delays is negligible when compared to the cost of serious conflicts.

Thus, out of the three options, it is recommended that CoEXist be used as the model for ConFAV driving behaviour.

4.5 Chapter Summary

Two published behaviour models (Atkins and CoEXist) were identified, and a third model (Tested Logic) was created, which takes into consideration varying driving behaviours of the ConFAV dependent on whether it is following another of its kind versus a conventional human driver with no data connectivity. The driving behaviours were tested using microsimulation on three types of junctions, designed to UK standards:

- Priority Junction
- Signal-controlled junction
- Roundabout

Rules were defined for each junction type within the simulation software based on the UK road rules and by adjusting the following:

- Vehicle input and route decision data.
- Desired speed distribution.
- Vehicle composition and relative flow.
- Junction right of way rules using conflict zones.
- Signal phases for the signal-controlled junction.

A comparison of the average change in delays experienced across all route movements within each junction type for all three models has highlighted that the Tested Logic behavioural model has performed the best in both the signal-controlled junction and roundabout, while Atkins performed the best within the priority junction. The CoEXist model was the worst performer but differed from the best performer by a maximum of only 3.21 percentage points.

A comparison of the change in the number of serious conflicts recorded across all route movements within each junction type for all three models has highlighted that the CoEXist behavioural model has performed the best in all junction types. The highest reduction in serious conflicts was observed within the roundabout, while the least was observed in the signal-controlled junction. The signal-controlled junction was the only one to experience an increase in the number of serious conflicts for the Atkins and Tested Logic behavioural models.

A recommendation was made to use the CoEXist model as the others had a high cost of potentially serious collisions while providing only a very small benefit in the reduction of average delays within the junction.

5. CASE STUDY: CONNECTED FAVS OPERATING WITHIN COMMUNITIES AROUND THE QUEEN ELIZABETH OLYMPIC PARK (QEOP), LONDON

5.1 Introduction and Outline

The Queen Elizabeth Olympic Park (QEOP) and environs (enclosed in purple in Figure 5-1 below) were first modelled in its entirety to determine which zones would require closer assessment. Two sites highlighted in red below were isolated and modelled as they represented the following transportation needs:

A. <u>Residential</u>: Hackney Wick

B. <u>Commercial</u>: Westfield

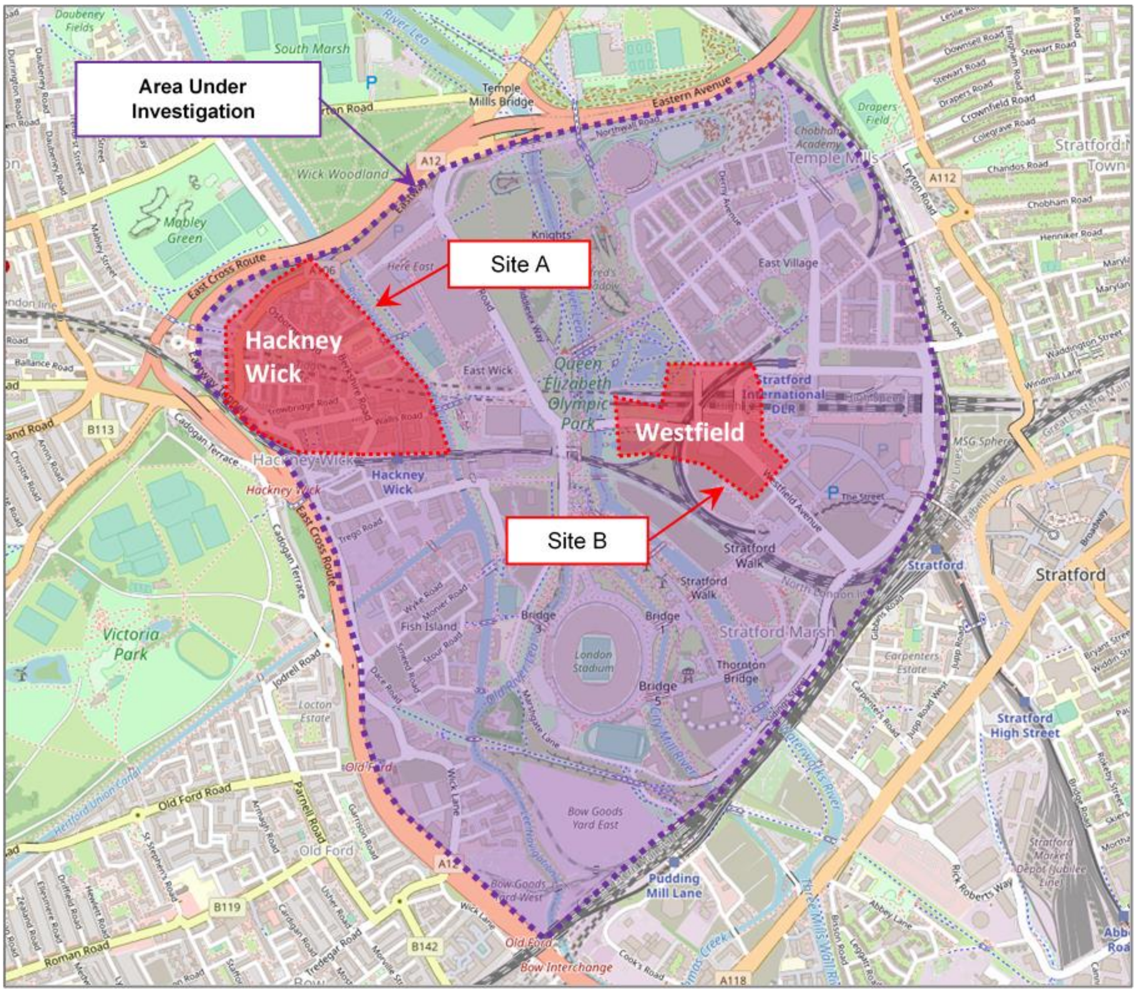


Figure 5-1 Study Area

5.1.1 Residential Area: Hackney Wick

Hackney Wick is an urban developing community that sits to the west of the Queen Elizabeth Olympic Park and the new communities of Eastwick and Sweetwater to the east and is within close proximity to the West Ham FBC Stadium, London Aquatics Centre, and the Westfield Shopping Centre (Europe's largest shopping mall). This community has grown in popularity since the London 2012 Olympics, attracting investment from different landowners, organisations, and government bodies.

The London Borough of Hackney's (LBoH) website (2021) highlights that Hackney Wick is known for its heritage of industry, enterprise, manufacture, and trade, and that the new Hackney Wick Neighbourhood Centre would be at the centre of one of London's first Creative Enterprise Zones. LBoH also revealed that Hackney Wick is categorised as a flourishing London quarter, characterised by exciting employment offers for local independent industry, creators, artists, and other creative businesses (LBoH, 2021). Recent and planned improvements to the area of interest is shown in Figure 5-2 below.

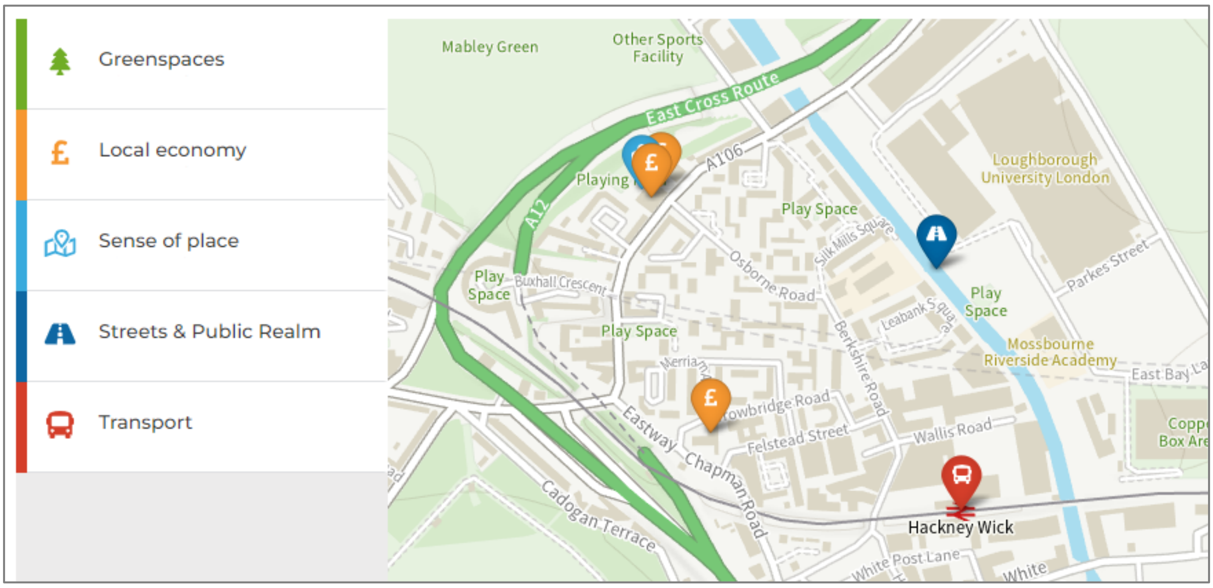


Figure 5-2 Recent and Planned improvements to the community

This section of the East-London community was chosen to be modelled as it represents all 3 junction types assessed in the previous chapter. The isolated network being modelled is shown bordered in purple, and the location of the 3 types of junctions monitored are marked with coloured dots. Orange for the priority junction type, blue for the signal-controlled junction type, and green for the roundabout junction type.

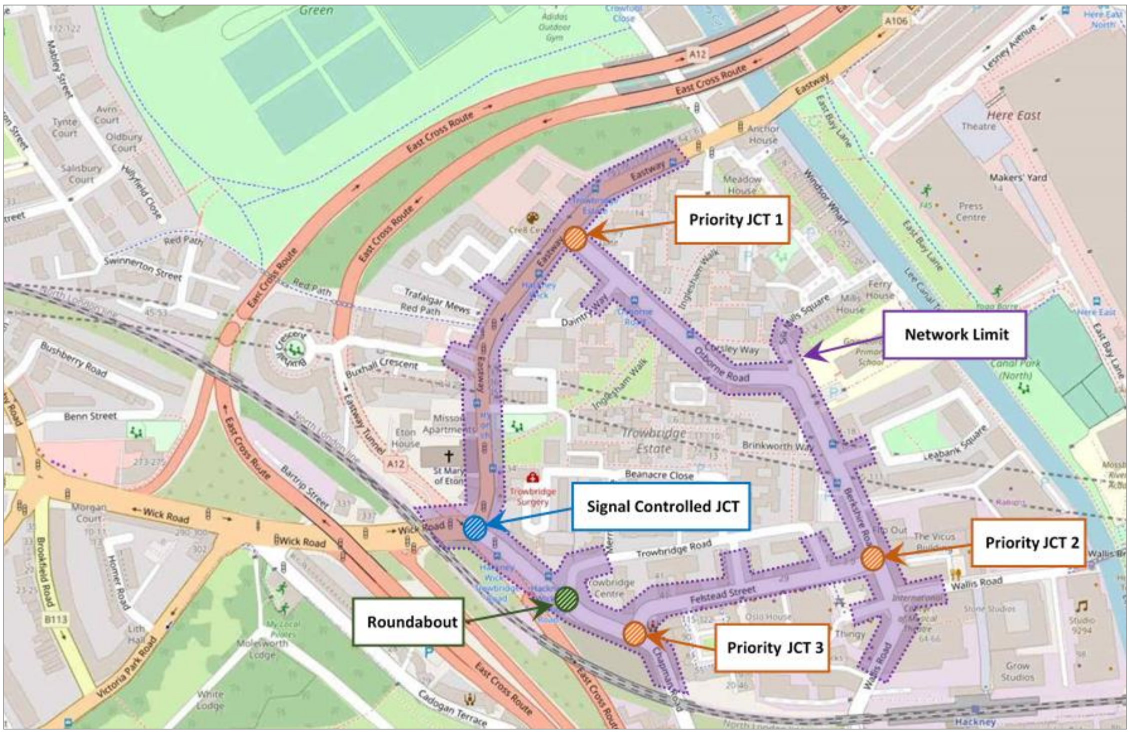


Figure 5-3 Junctions being assessed within the network limits

5.1.2 Commercial Area: Westfield

Site B (Figure 5-4 below) was selected because of the access to Westfield and the major transport link to Stratford International. The Stratford underground station is also accessible through Westfield and also by continuing south along Westfield Avenue, so this station could impact travel demand of this site.

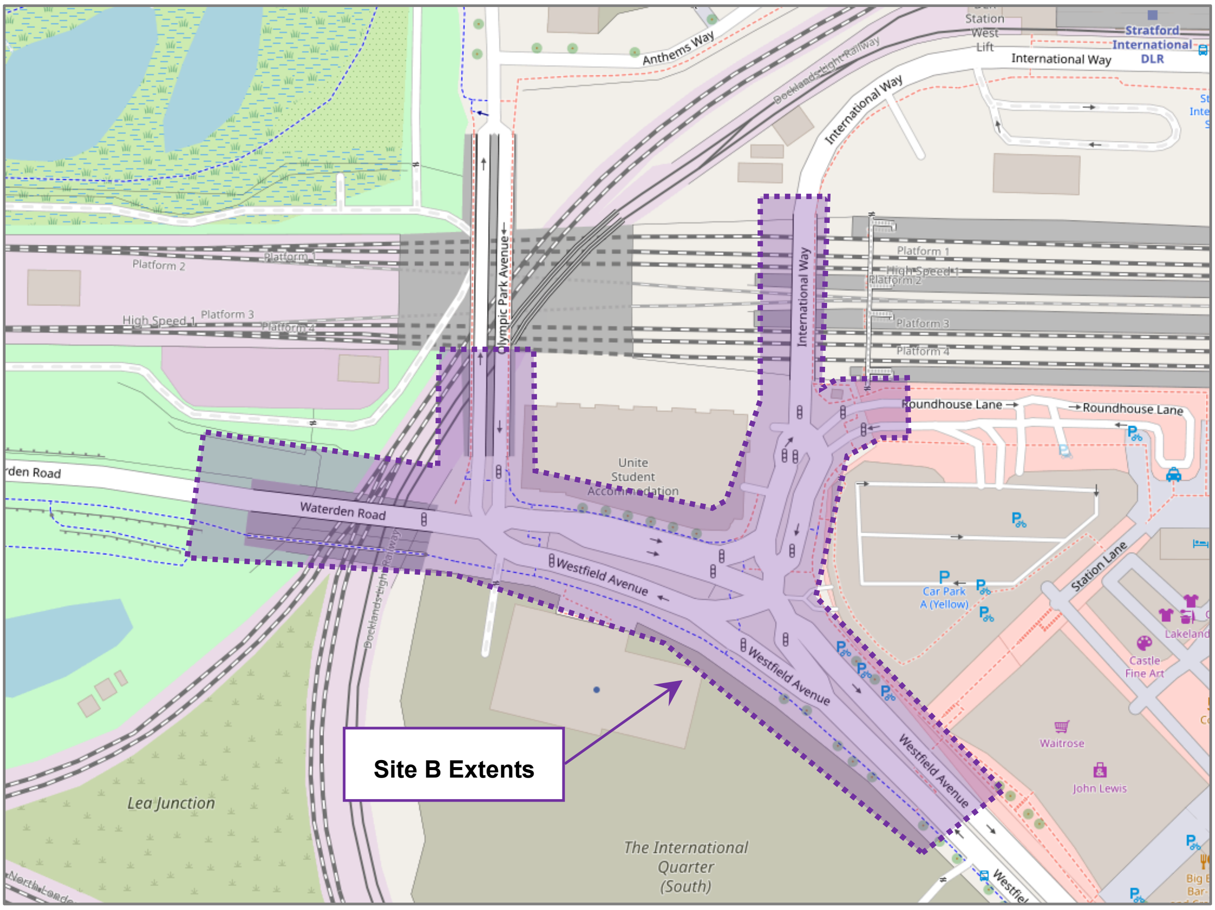


Figure 5-4 Site B Extents - Commercial Area: Westfield

5.1.3 <u>Chapter Outline:</u>

This chapter will evaluate the safety performance and efficiency of the two isolated areas within the QEOP and surroundings, using the CoEXist behaviour model tested in the previous chapter, documenting the impact the different penetration levels may have of the network.

The remainder of the chapter will be broken down as follows:

- Site A Microsimulation Methodology
- Site B Microsimulation Methodology
- Findings & Analysis Site A
- Findings & Analysis Site B
- Discussion & Conclusions
- Chapter Summary

5.2 Site A Microsimulation Methodology

5.2.1 Network Geometry

In this experiment, the layout was designed using the existing footprint of the road network shown below, within the limits highlighted in purple. The simulation monitors three priority junctions, one signal-controlled junction and one roundabout. These are shown in Figure 5-5 below.

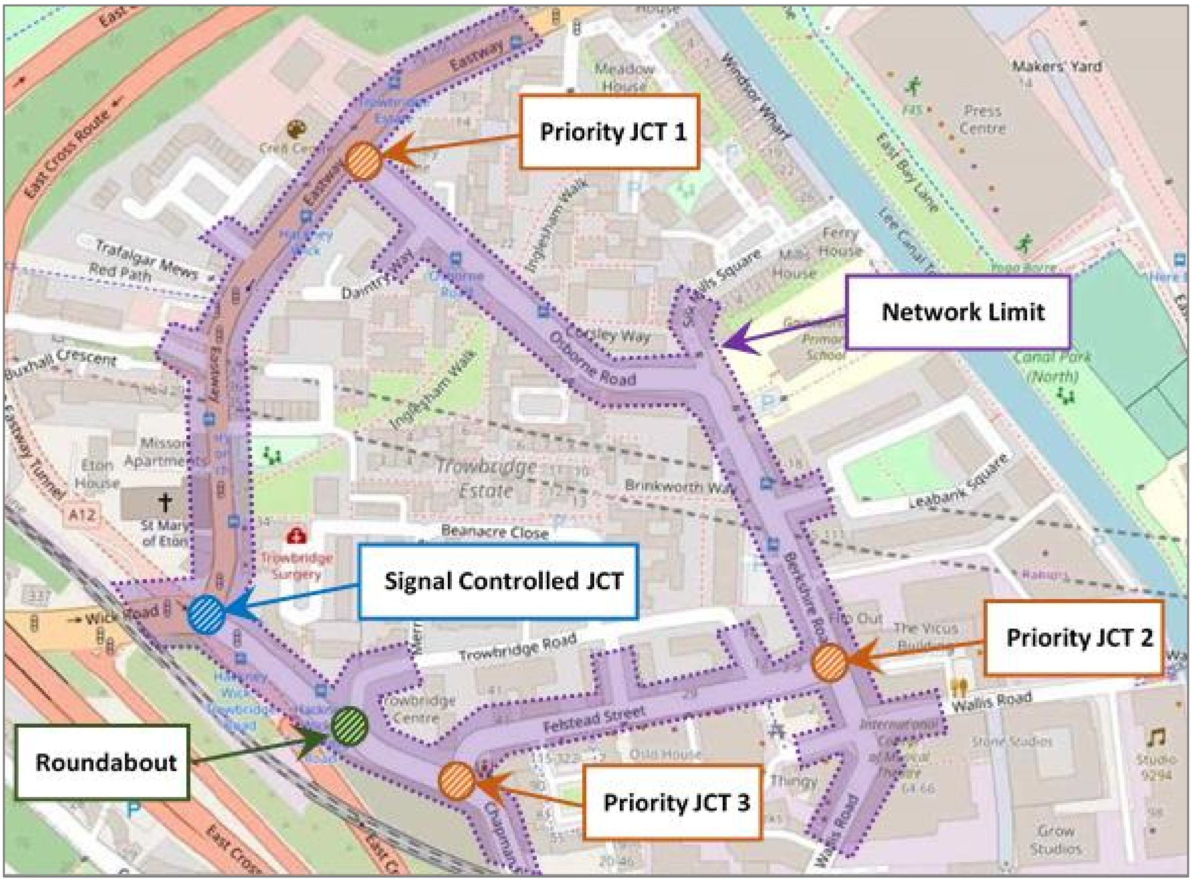


Figure 5-5 Junction types

5.2.2 Vehicle Input and Route Decisions:

Vehicle Entry Points

In this network, there are 4 main entry points (highlighted in green on Figure 5-6 below) and 13 minor points (highlighted in yellow on Figure 5-6 below), which are either individual property access points (gated & non-gated), or access to developments.

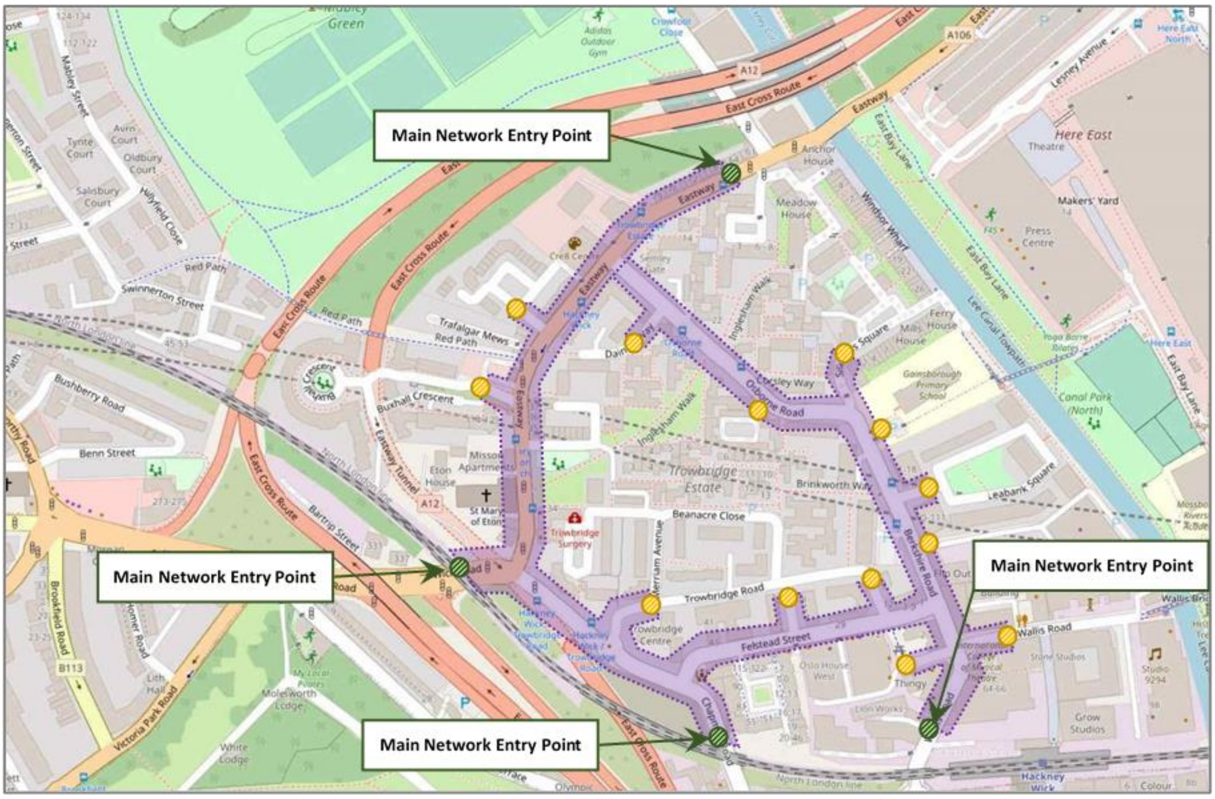


Figure 5-6 Network entry points

Network Vehicle Input

The values used for the hourly vehicle input for the four main network entry points were taken as an average of the raw vehicle data collected at the Department for Transport (DfT) count points that fell within the study area. Their approximate locations are shown as a green circle on the map in Figure 5-7 below.

The raw vehicle data for cars passing the count points were taken between the hours of 11:00 and 13:00 for the 2 most recent years available. ***It must be noted that data for 2020 was ignored as the traffic volumes were impacted due to the***

unprecedented nationwide lockdown limiting travel, which was in force at the time.

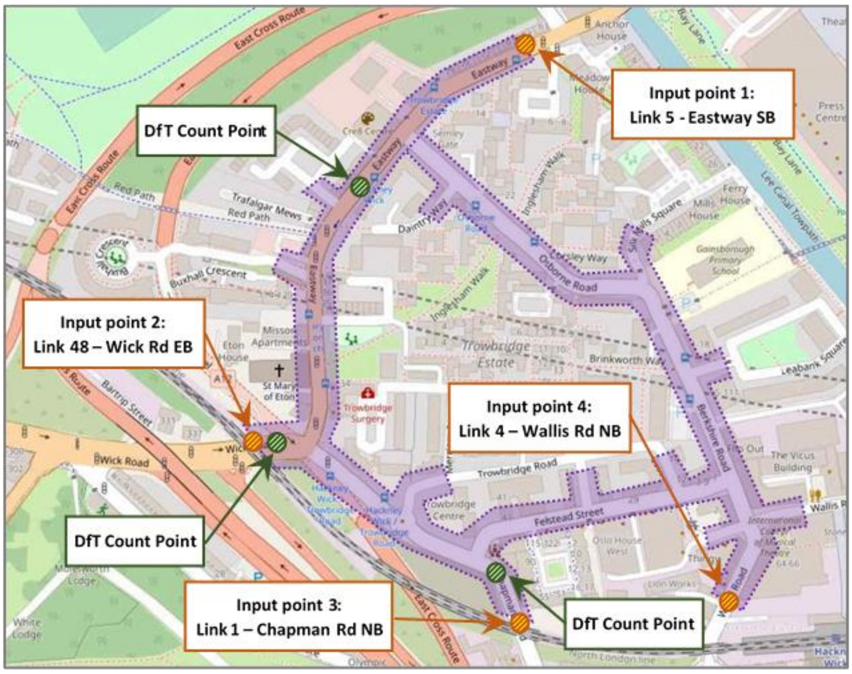


Figure 5-7: DfT Count Points

There were no count points available near input point 4, so an estimate was used based on similar counts in neighbouring areas as indicated in Table 5-1 below.

Table 5-1 Site A vehicle input volume

Input Point	Average Veh/hr recorded between 11:00 & 13:00 at Count Point	Calibrated Veh Input Volume
Input point 1: Link 5 - Eastway SB	432 Veh/hr	432 Vehs/hr
Input point 2: Link 48 – Wick Rd EB	731 Veh/hr	731 Vehs/hr
Input point 3: Link 1 – Chapman Rd NB	257 Vehs/hr	257 Veh/hr
Input point 4: Link 4 – Wallis Rd NB	No data - Estimate	250 Veh/hr

Vehicle Route Decisions

Vehicle routes were more intricate to calibrate, as this was done for every junction, network entry point, and access point. There was a total of 49 route decisions programmed within the software, which are shown in table C-1 of Appendix C.

5.2.3 *Existing Conditions:*

The roads within the study area of Site A were classified as UAP4 (according to TA 79/99) in this experiment, as there were frequent at-grade pedestrian crossings, kerbside bus stops, lots of local traffic, and also unlimited access to houses, shops, and businesses. The estimated RFC values based on the calibrated flow and the UAP4 capacity classification are shown in Table 5-2 below.

During the visit to Site A, queuing was observed at the signalised junction at input point 2. All other junctions appeared to flow normally.

Table 5-2 Site A RFC Values

Input Point	Calibrated Veh Input Volume	**Ratio of Flow to Capacity (RFC)**
Input point 1: Link 5 - Eastway SB	432 Vehs/hr	0.38
Input point 2: Link 48 – Wick Rd EB	731 Vehs/hr	0.64
Input point 3: Link 1 – Chapman Rd NB	257 Veh/hr	0.23
Input point 4: Link 4 – Wallis Rd NB	250 Veh/hr	0.22

Safety Observations*:*

Personal injury collisions (PICs) within the boundary of Site A were investigated for the 5-year period of January 2015 to December 2019. There were no fatal PICs were recorded within the boundary, but 30% of all collision were of a serious nature. There were no obvious trends or hotspots within the area. This is demonstrated in Figure 5-8 below.

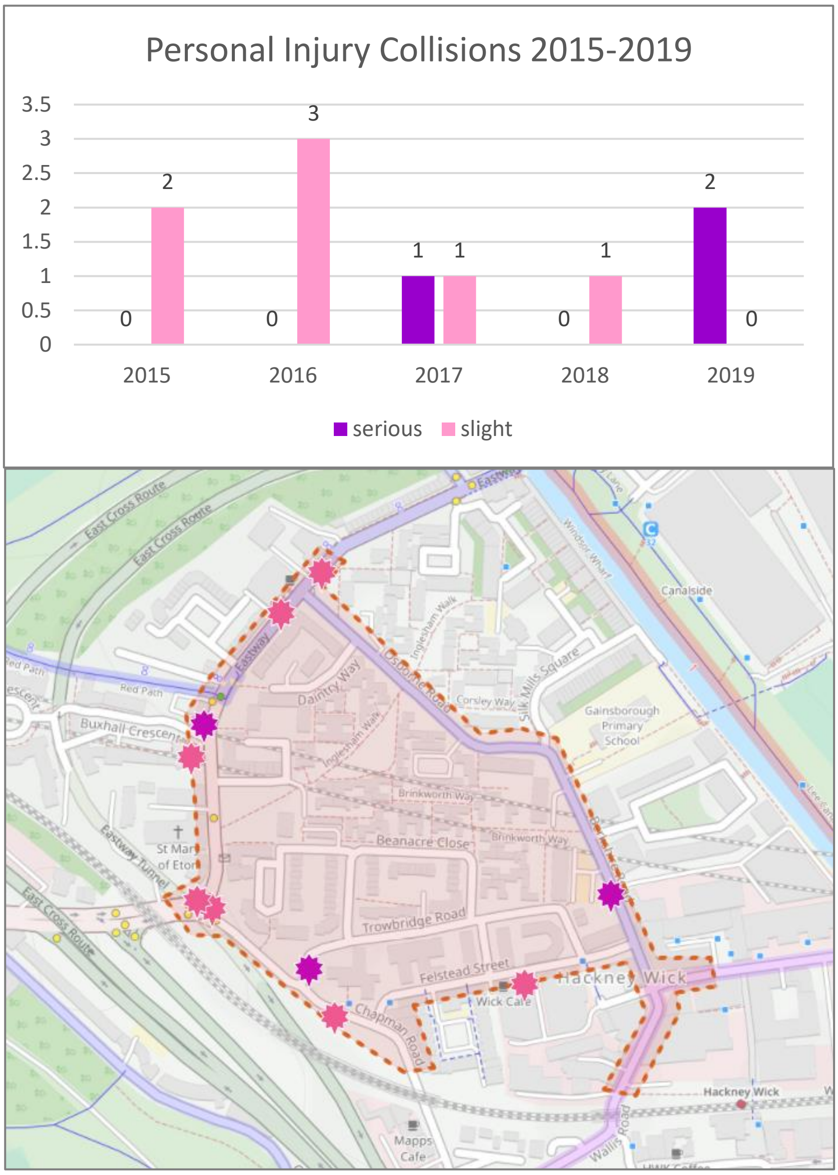


Figure 5-8: DfT Personal Injury Collision Data 2015-2019 (Cyclestreets.net, 2022)

5.2.4 <u>Vehicle Composition and Relative Flows:</u>

The model was run at 20% iterations. The penetration rate of the fully autonomous vehicle was modelled using the relative flow distribution table shown below.

Table 5-3 Vehicle composition and relative flow distribution table

FAV %	Vehicle Type	Desire Speed Distribution	Relative Flow
0% FAV Penetration	Car	Car 20 mph zone	1.000
	ConFAV	FAV 20 zone	0.000
20% FAV Penetration	Car	Car 20 mph zone	0.800
	ConFAV	FAV 20 zone	0.200
40% FAV Penetration	Car	Car 20 mph zone	0.600
	ConFAV	FAV 20 zone	0.400
60% FAV Penetration	Car	Car 20 mph zone	0.400
	ConFAV	FAV 20 zone	0.600
80% FAV Penetration	Car	Car 20 mph zone	0.200
	ConFAV	FAV 20 zone	0.800
100% FAV Penetration	Car	Car 20 mph zone	0.000
	ConFAV	FAV 20 zone	1.000

5.2.5 <u>Desired Speed distribution and Reduced Speed Zones:</u>

This area is built-up and as such the speed limit for the network to 20 mph and are distributed as shown in the table below.

Table 5-4 Speed distributions for 20mph zone

Conventional Vehicles		Connected FAVs	
Speed (miles per hour)	Distribution	Speed (miles per hour)	Distribution
18 mph	0.00	19.99 mph	0.00
20 mph	0.14	20.00 mph	1.00
26 mph	1.00	----	----

Vehicles doing a U-turn are modelled to do so using a lower desired speed distribution of 10 mph, using the same distributions as the reduced speed zones in the previous section, as shown in the table below.

Table 5-5 Desired Speed Distribution for 10mph

Conventional Vehicles		Connected FAVs	
Speed (miles per hour)	Distribution	Speed (miles per hour)	Distribution
7.46 mph	0.00	9.99 mph	0.00
11.00 mph	1.00	10.00 mph	1.00

The deceleration within these reduced speed zones for Fully autonomous car will be the same as conventional cars, which is capped at 2.

Table 5-6 Reduced Speed zones

Vehicle Class	Desire Speed Distribution	Deceleration
Car	10 mph U-Turn	2.00
ConFAV	10 mph FAV U-Turn	2.00

5.2.6 *Modelling Right of Way*

As mentioned previously, this network had three types of junctions: Priority Junction, Signal-controlled Junction, and Roundabout. This means that right of way was modelled differently depending on the junction type.

Priority Junction & Roundabout

Right of way was modelled within roundabouts and priority junctions using conflict zones. Vehicles on the same link, mutually observe each other, and so only those that cross each other paths were considered in this experiment. In branching conflicts, all vehicles acknowledge each other but there is no right of way (R.O.W.), and vehicles remain in their original sequence.

The table below shows an example of conflict zones within the model. A full list of zones and their statuses is shown in Appendix G..

Table 5-7 Excerpt from the Conflict Zone Statuses used in the model

LINK 1	LINK 2	STATUS
25: Eastway NB	10011: chapman to eastway NB	Passive
21: Osborne Rd NB	10042: daintry to osborne RT	2 waits for 1
22: Osborne Rd SB	10044: osborne to daintry SB RT	Passive
10042: daintry to osborne RT	10044: osborne to daintry SB RT	1 waits for 2

Signal-Controlled Junction

The signal programme shown in the image below, directed the traffic flow for the junction. The programme featured two groups whose signal sequences included 4 signal types: Red, red & amber, green, and amber. A third group featured a permanent green, which allowed eastbound traffic from Wick Road to turn left on to Eastway unrestricted (shown in Figure 5-9). The locations of the assigned signal groups are shown in Figure 5-10 below.

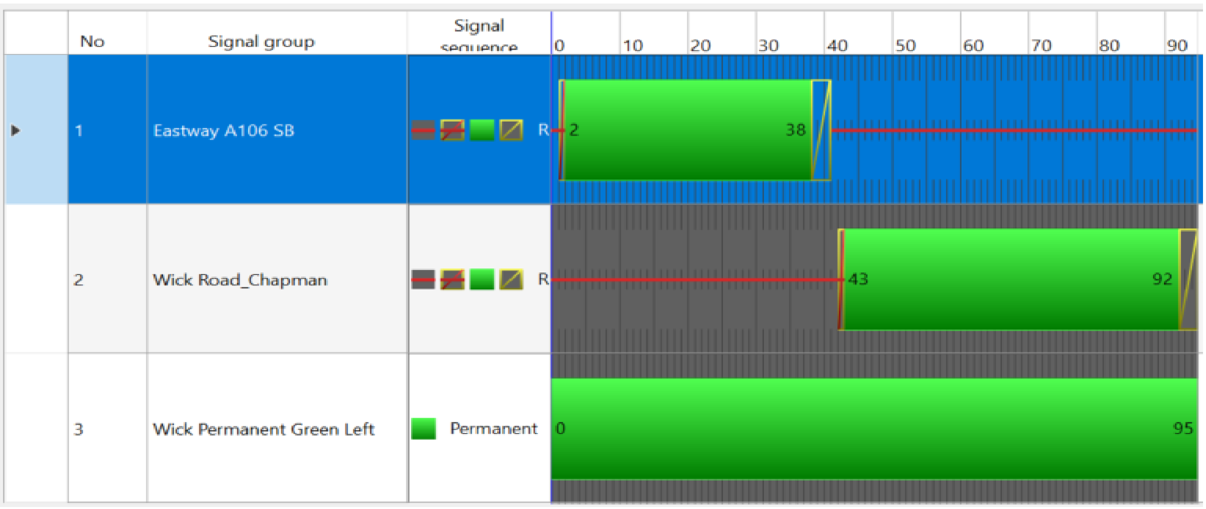


Figure 5-9 Signal Groups for Signal-controlled junction

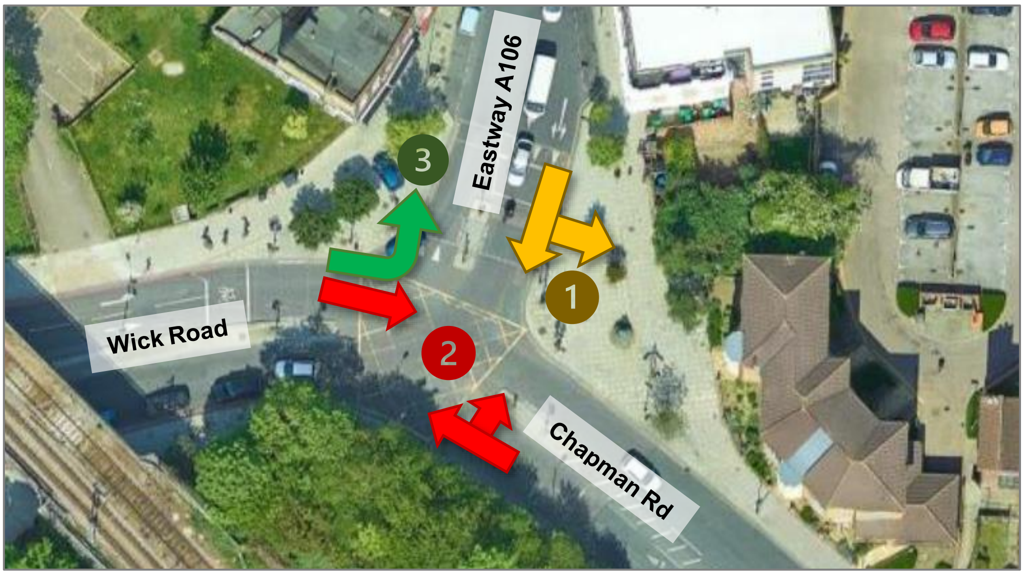


Figure 5-10 Location of the assigned signal groups

5.3 Site B Microsimulation Methodology

5.3.1 Network Geometry

In this experiment, the layout was designed using the existing footprint of the road network shown below, simulating a combination of three signal-controlled junctions.

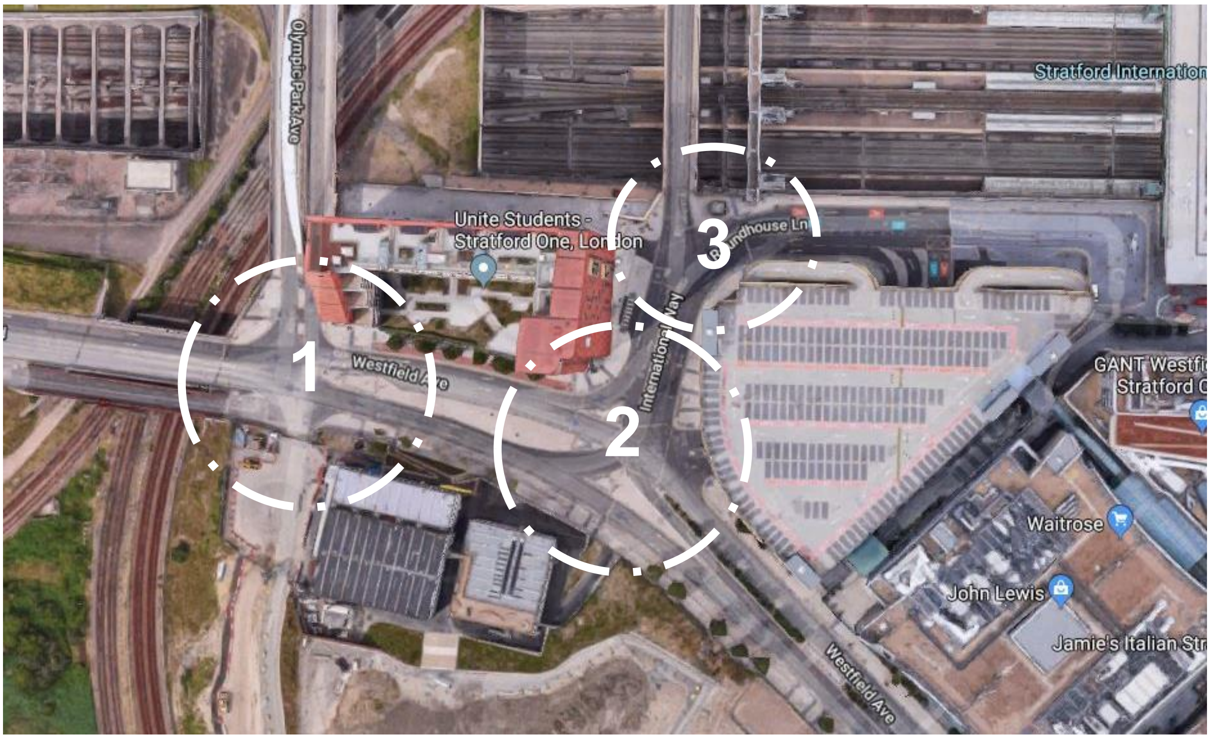


Figure 5-11 Aerial shot of existing layout (Google, 2018)

5.3.2 Vehicle Input and Route Decisions:

In this network, there are 5 entry points and 5 exit points. U-Turns are not permitted at any of these junctions, and so this was not accounted for in the route decisions as shown below.

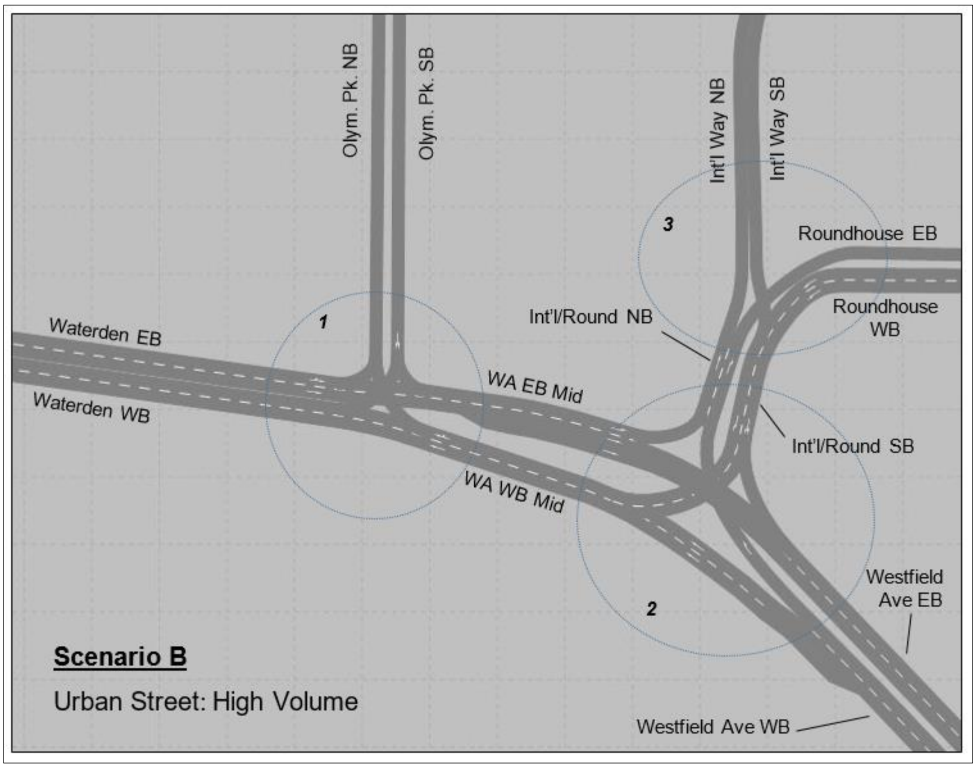
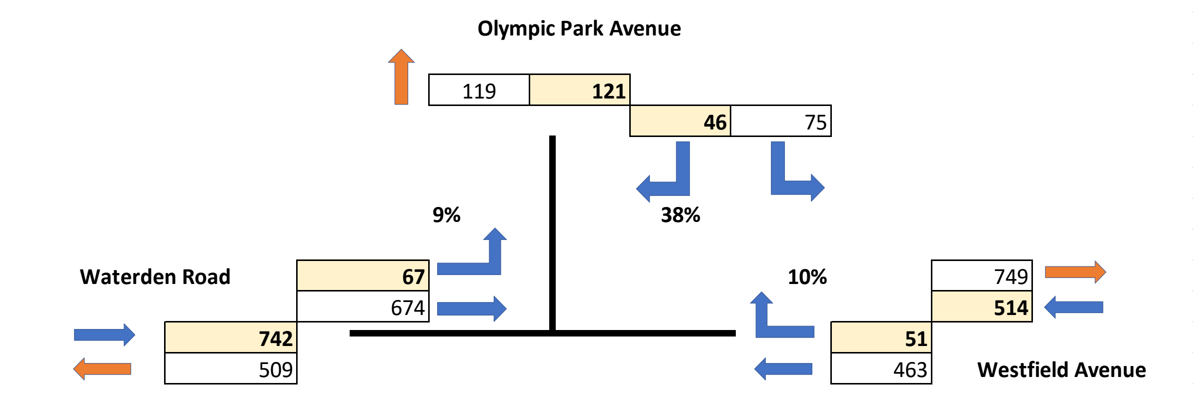


Figure 5-12 Layout of links in road network

Junction 1

Table 5-8: Site B junction 1 Route decisions

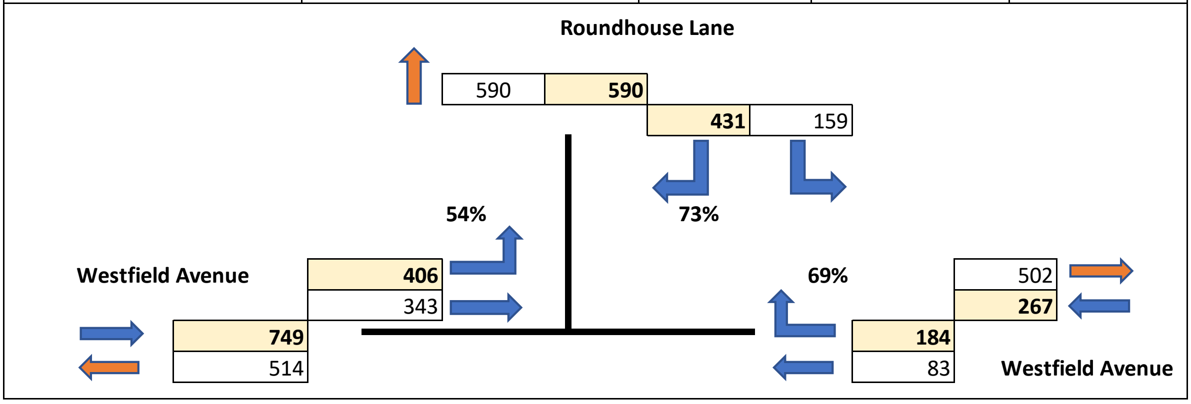
Link	Veh Input Vol	Route Decision		
Waterden EB	742 Vehs/hr	Left Turn	Through	Right Turn
		9%	91%	---
Olympic Pk. SB	121 Vehs/hr	Left Turn	Through	Right Turn
		62%	---	38%
WA WB Mid	No input value programmed	Left Turn	Through	Right Turn
		---	90%	10%



Junction 2

Table 5-9: Site B junction 2 Route decisions

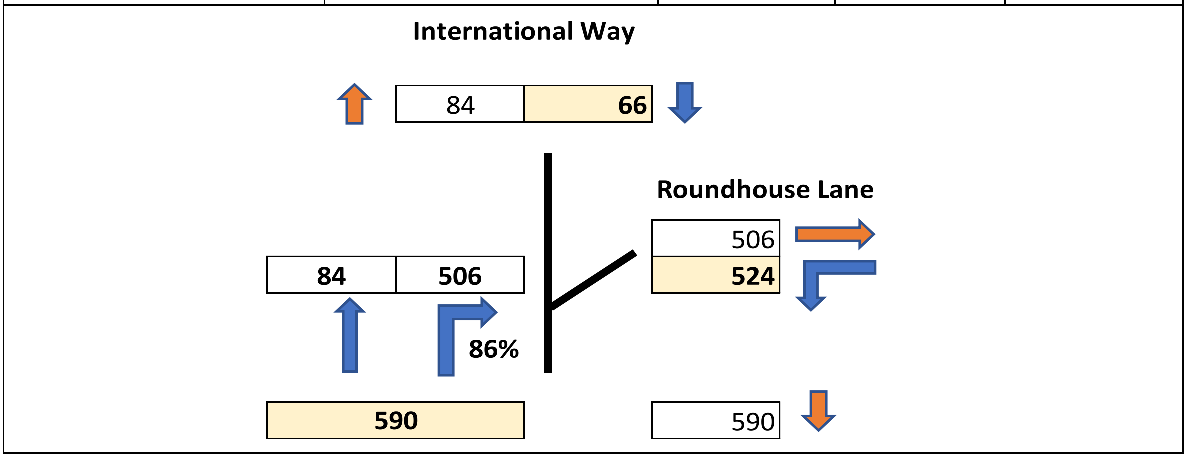
Link	Veh Input Vol	Route Decision		
WA EB Mid	No input value programmed	Left Turn	Through	Right Turn
		54%	46%	---
Int'l/Round SB	No input value programmed	Left Turn	Through	Right Turn
		27%	---	73%
Westfield Ave WB	267 veh/hr	Left Turn	Through	Right Turn
		---	31%	69%



Junction 3

Table 5-10: Site B junction 3 Route decisions

Link	Veh Input Vol	Route Decision		
Roundhouse WB	524 Vehs/hr	Left Turn	Through	Right Turn
		100%	---	---
Int'l/Round NB	No input value programmed	Left Turn	Through	Right Turn
		---	14%	86%
Int'l Way SB	66 Vehs/hr	Left Turn	Through	Right Turn
		---	100%	---



5.3.3 <u>Existing Conditions:</u>

Roads within the Site B case study were classified as Urban All-Purpose roads, with restricted parking and loading, more than 2 side roads per kilometre, some at-grade pedestrian crossings, and bus stops at kerbside. According to TA 79/99, the road type would be classified as UAP2.

The estimated RFC values based on the calibrated flow and the UAP2 capacity classification are shown in Table 5-11 below. During the visit to Site B, traffic flow appeared normal with no excess congestion. Small queues were observed waiting at traffic signals.

Table 5-11 Site A RFC Values

Input Point	Carriageway	Calibrated Veh Input Volume	Ratio of Flow to Capacity (RFC)
Waterden EB	Single (4 Lanes)	742 Vehs/hr	0.35
Olympic Pk. SB	Single (2 lanes)	121 Vehs/hr	0.08
Westfield Ave WB	Dual (2 Lanes per direction)	267 Vehs/hr	0.08
Roundhouse WB	Single (3 lanes)	524 Vehs/hr	0.31
Int'l Way SB	Single (2 lanes)	66 Vehs/hr	0.04

<u>Safety Observations</u>*:*

Personal injury collisions (PICs) within the boundary of Site B were investigated for the 5-year period of January 2015 to December 2019. There were no fatal PICs recorded within the boundary, but 20% of all collision were of a serious nature.

Collisions only appeared to occur at junctions 1 and 2 within the study area, during that time period. This is demonstrated in Figure 5-13 below.

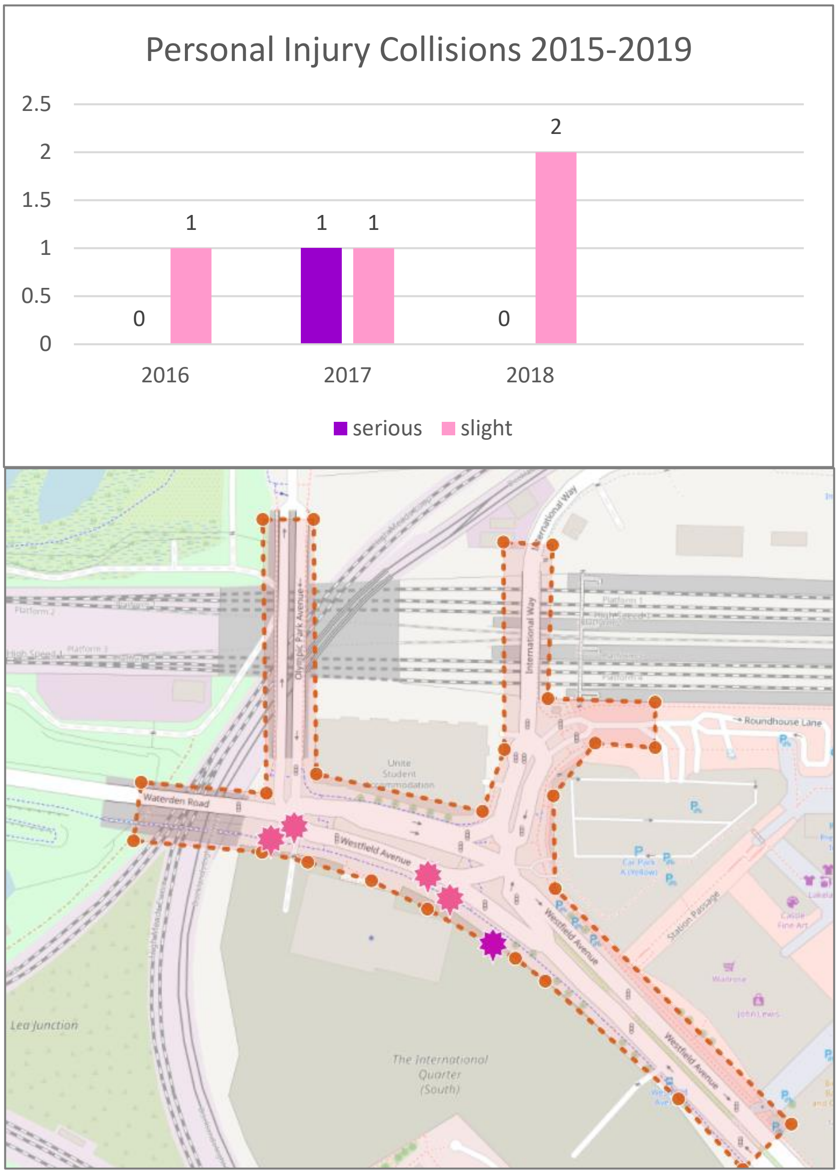


Figure 5-13: DfT Personal Injury Collision Data 2015-2019 (Cyclestreets.net, 2022)

5.3.4 *Vehicle Composition and Relative Flows:*

The model was run at 20% iterations. The penetration rate of the fully autonomous vehicle was modelled using the relative flow distribution table shown below.

FAV %	Vehicle Type	Desire Speed Distribution	Relative Flow
0% FAV Penetration	Car	Car 20 mph zone	1.000
	ConFAV	FAV 20 zone	0.000
20% FAV Penetration	Car	Car 20 mph zone	0.800
	ConFAV	FAV 20 zone	0.200
40% FAV Penetration	Car	Car 20 mph zone	0.600
	ConFAV	FAV 20 zone	0.400
60% FAV Penetration	Car	Car 20 mph zone	0.400
	ConFAV	FAV 20 zone	0.600
80% FAV Penetration	Car	Car 20 mph zone	0.200
	ConFAV	FAV 20 zone	0.800
100% FAV Penetration	Car	Car 20 mph zone	0.000
	ConFAV	FAV 20 zone	1.000

Table 5-12: Vehicle composition and relative flow distribution table

5.3.5 *Desired Speed distribution and Reduced Speed Zones:*

This area is built-up and as such the speed on the link is limited to 20 mph and are distributed as shown in the table below.

Table 5-13: Speed distributions for 20mph zone

Conventional Vehicles		Connected FAVs	
Speed (miles per hour)	Distribution	Speed (miles per hour)	Distribution
18 mph	0.00	19.99 mph	0.00
20 mph	0.14	20.00 mph	1.00
26 mph	1.00	----	----

Vehicles doing a U-turn are modelled to do so using a lower desired speed distribution of 10 mph, using the same distributions as the reduced speed zones in the previous section, as shown in the table below.

Table 5-14: Desired Speed Distribution for 10mph

Conventional Vehicles		Connected FAVs	
Speed (miles per hour)	Distribution	Speed (miles per hour)	Distribution
7.46 mph	0.00	9.99 mph	0.00
11.00 mph	1.00	10.00 mph	1.00

The deceleration within these reduced speed zones for Fully autonomous car will be the same as conventional cars, which is capped at 2.

Table 5-15: Reduced Speed zones

Vehicle Class	Desire Speed Distribution	Deceleration
Car	10 mph U-Turn	2.00
ConFAV	10 mph FAV U-Turn	2.00

5.3.6 Modelling Right of Way

This network was governed by 2 signal programmes. The first signal programme is shown in the image below, directed the traffic flow for junctions 1 and 2. This included all traffic entering and leaving the main arteries, Westfield Avenue and Waterden Road. This programme oversaw 8 signal groups all working in tandem with each other. The geographic location of each of these signal heads and the corresponding signal group is shown in Figure 5-14 and Figure 5-15 below.

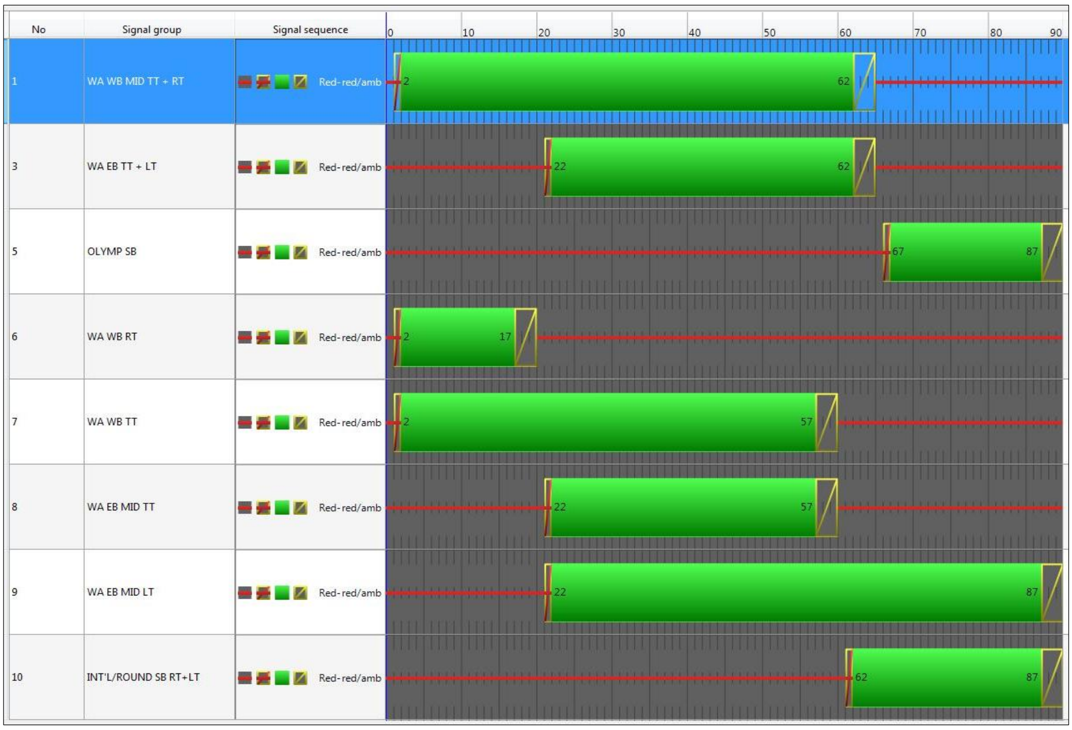


Figure 5-14 Signal Program for 90 Seconds Phase Cycle

The geographic location of each of these signal heads and the corresponding signal group is shown in the images and sequence tables below.

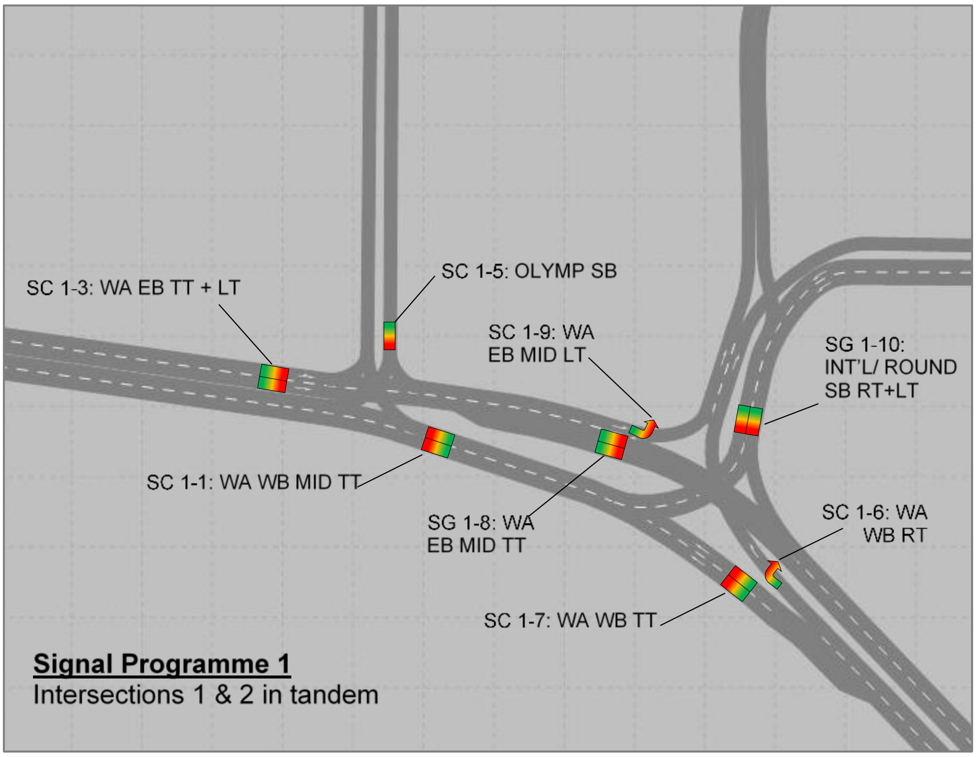


Figure 5-15 Signal Program for 90 Seconds Phase Cycle

Table 5-16 Sequence durations for signal groups

	Red	Amber & Red	Green	Amber
SC 1-1: WA WB MID TT	26	1	60	3
SC 1-3: WA EB TT + LT	46	1	40	3
SC 1-5: OLYMP SB	66	1	20	3
SC 1-6: WA WB RT	71	1	15	3
SC 1-7: WA WB TT	31	1	55	3
SC 1-8: WA EB MID TT	51	1	35	3
SC 1-9: WA EB MID LT	21	1	65	3
SC 1-10: INT'L/ ROUND SB RT+LT	61	1	25	3

This programme has 3 clear phases where three or more links are given the green signal to go. Two phases controlled the major links with a higher density, and the third phase controlled the 2 minor links with a lower volume of traffic.

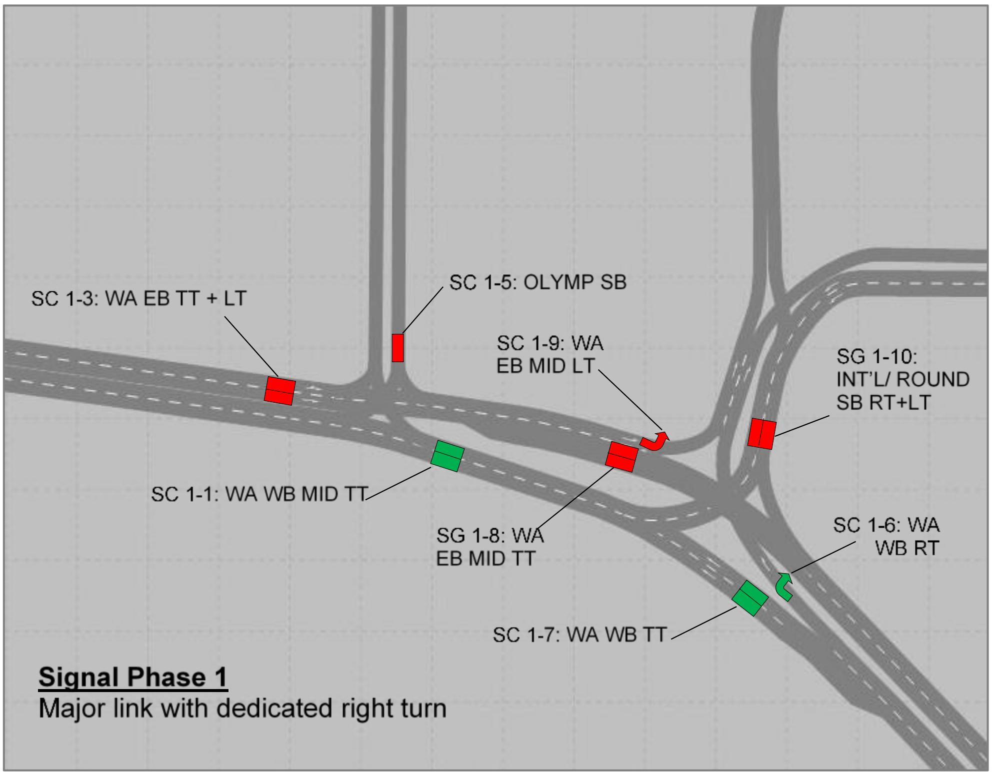


Figure 5-16 Signal Phase 1

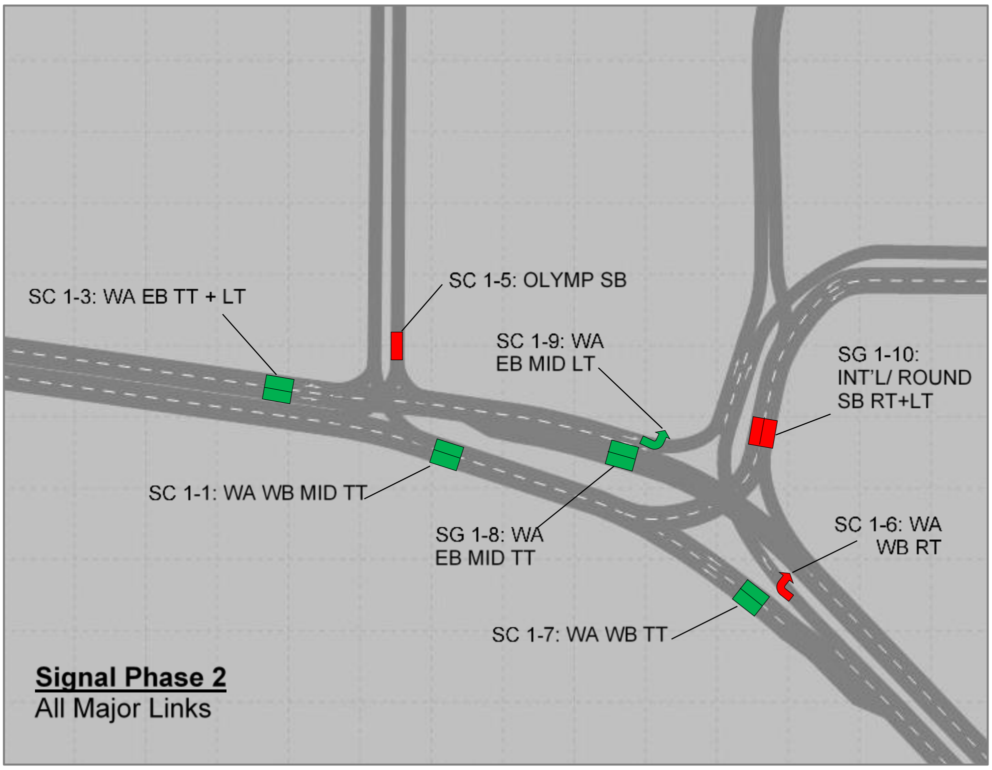


Figure 5-17 Signal Phase 2

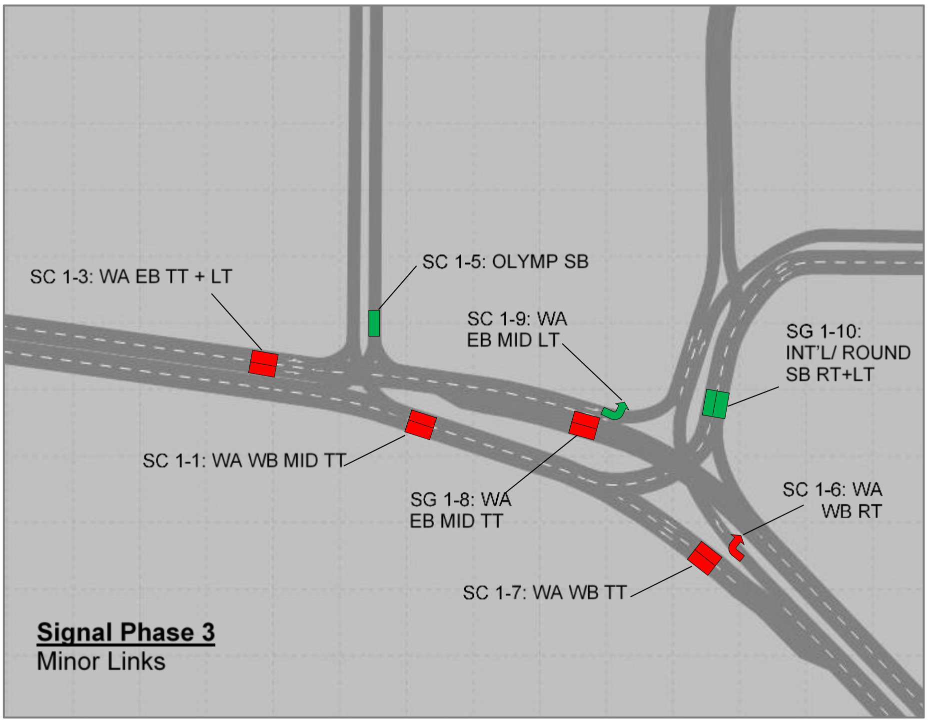


Figure 5-18 Signal Phase 3

The second signal programme used was one that included four (4) signal groups, and governed junction 3. This was done using a 60-seconds phase cycle. This is shown in Figure 5-19below.

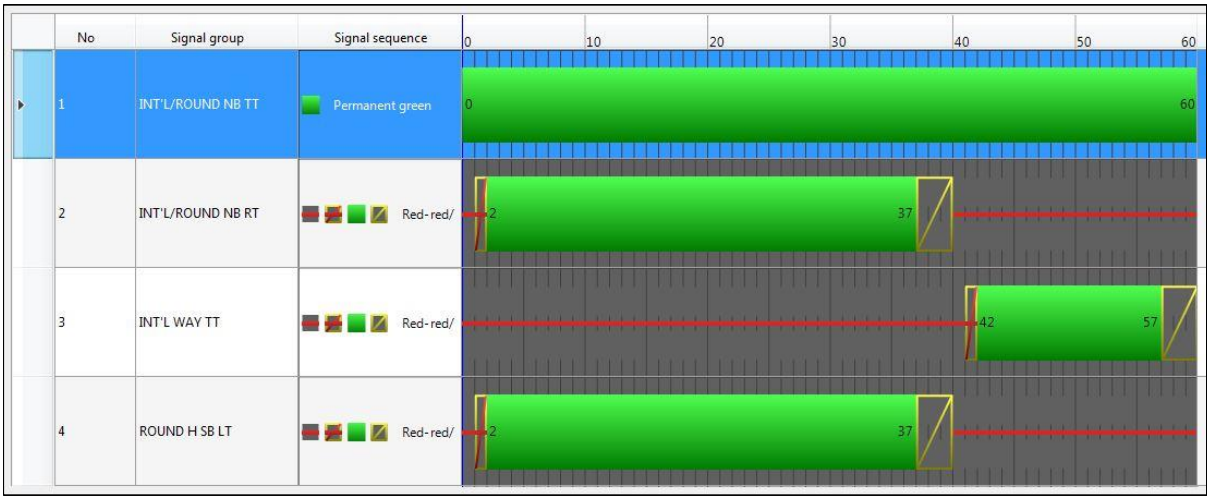


Figure 5-19 Signal Programme 2

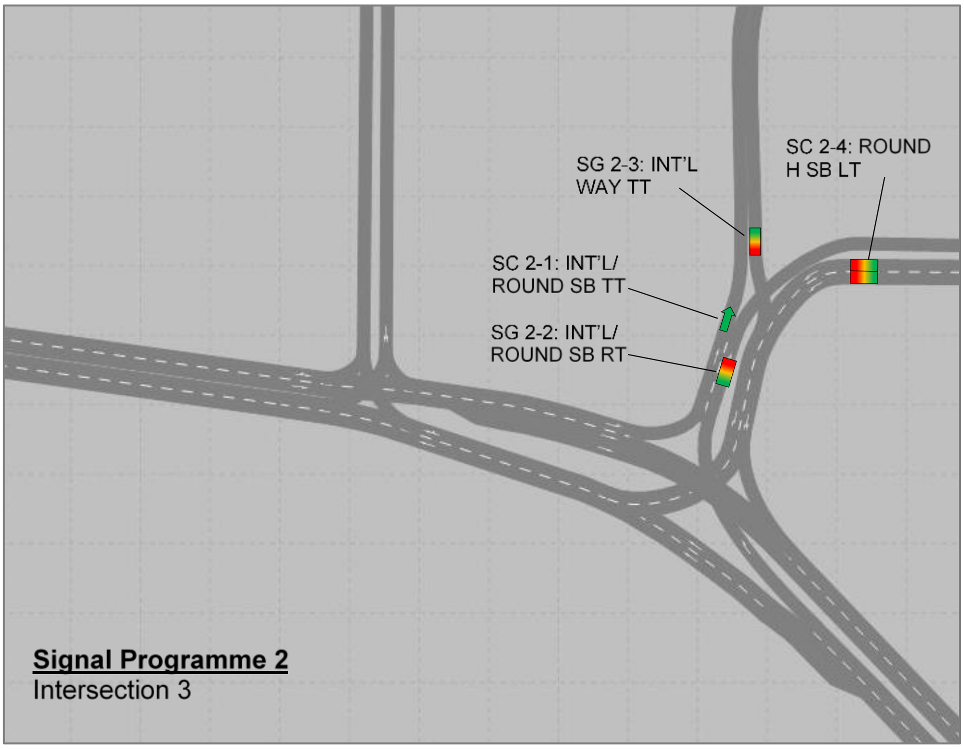


Figure 5-20 Signal Program 2 - 60 Seconds Phase Cycle

This programme has two (2) clear phases where two or more links are given the green signal to go. One link was on permanent green (SC 2-1) as there were no possible conflicts with other road users.

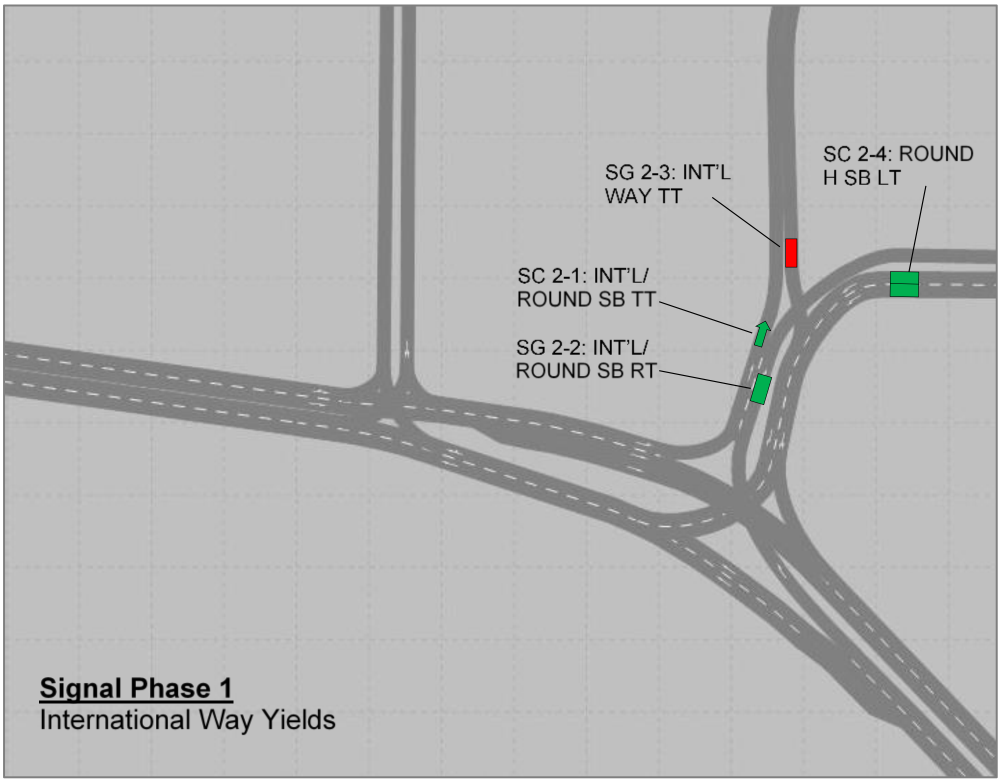


Figure 5-21 Signal Phase 1

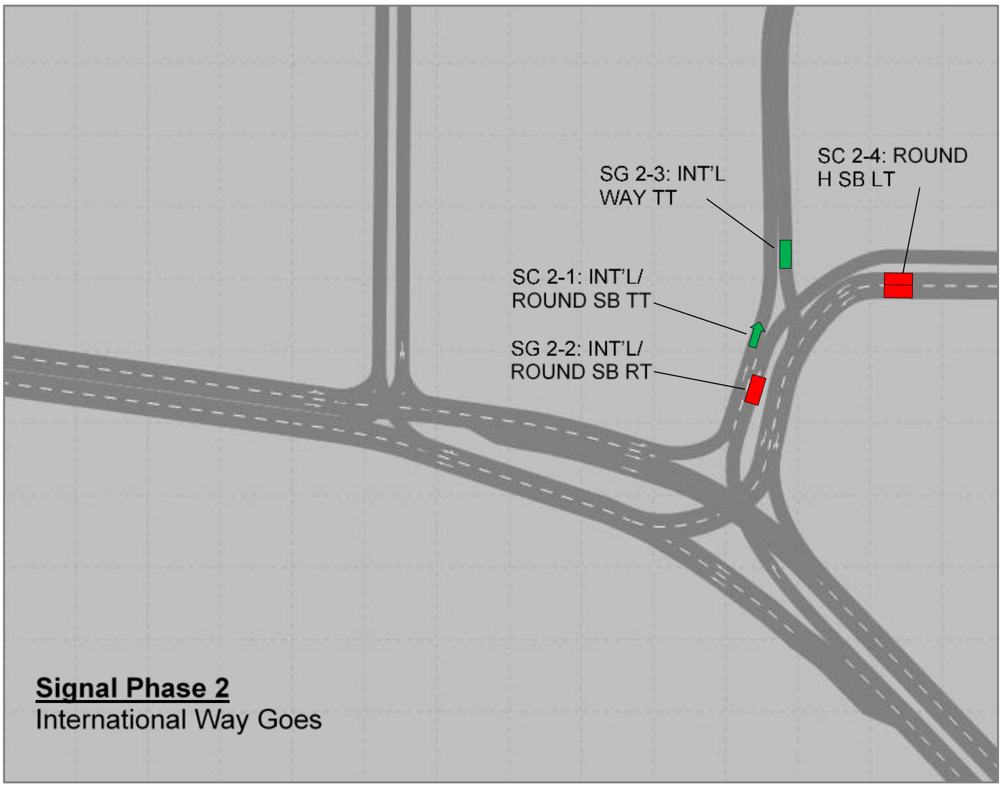


Figure 5-22 Signal Phase 2

5.4 Findings and Analysis for Site A: Hackney Wick

5.4.1 *Congestion Performance: Vehicle Delay & Network LOS*

There were six (6) junctions analysed within the network:

- 3 x Priority Junctions
- 1 x Signal Controlled Junction
- 1 x Roundabout

The locations of these junctions are marked out in the figure below.

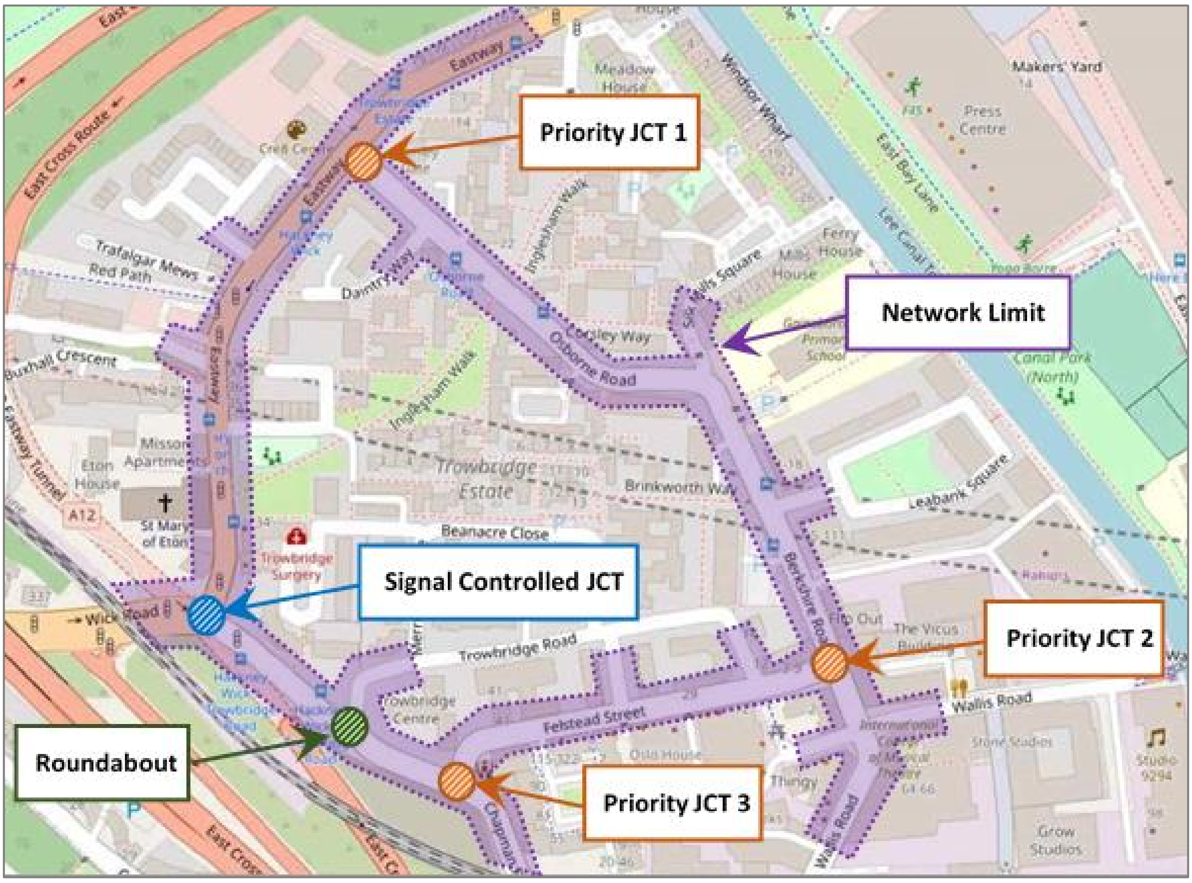


Figure 5-23 Junctions types

There was a total of 33 movements tested within the network: Six (6) movements within each priority junction, 9 within the roundabout, and 6 within the signal-controlled junction. These movements are illustrated for each junction in Figure 5-24 to Figure 5-26 below.

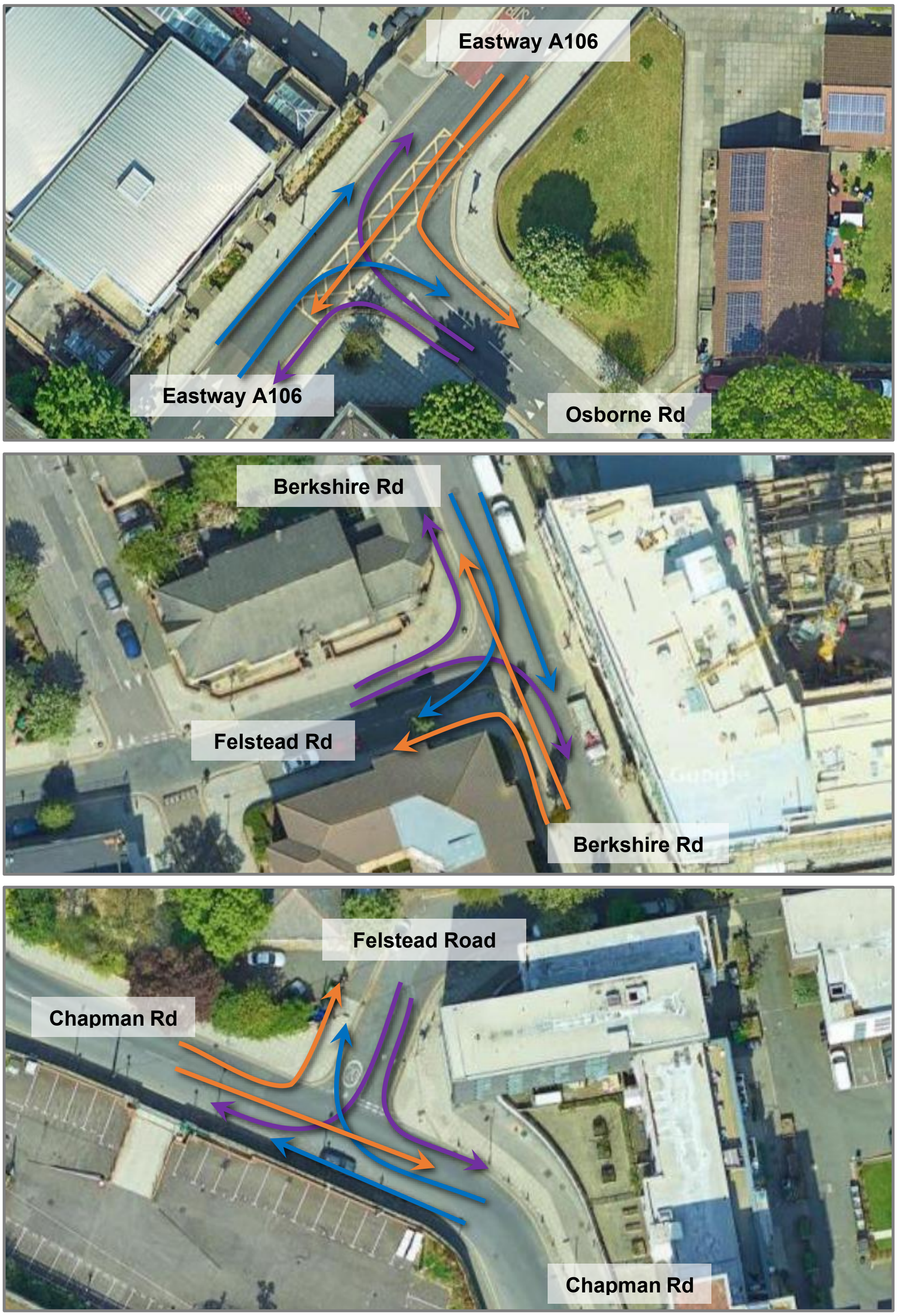


Figure 5-24: Movements within the 3 Priority Junctions

Figure 5-25: Movements within Roundabout

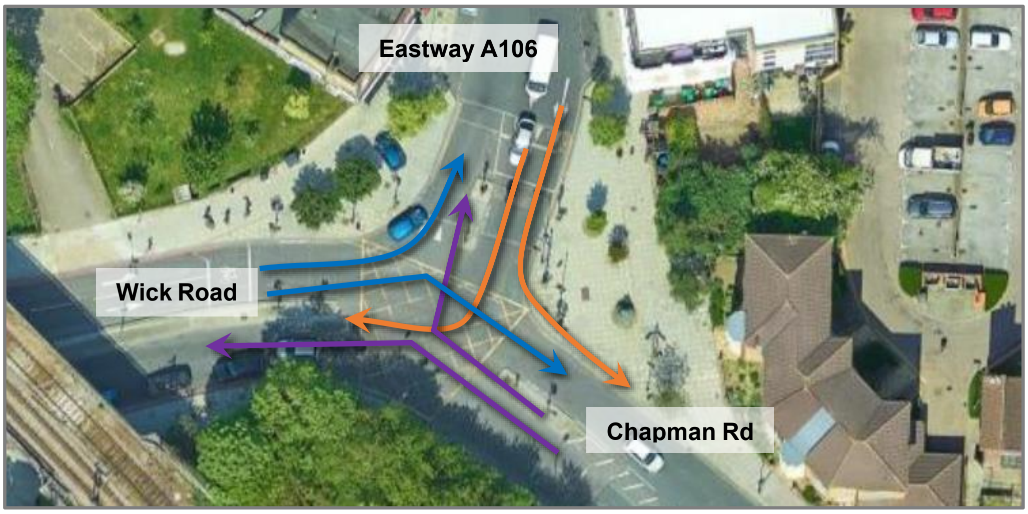


Figure 5-26: Movements within Signal-Controlled Junction

The average vehicle delay over the 2 hours simulation time along all 33 routes identified within network was compared for the six (6) ConFAV penetration levels, and the percentage change in the recorded average delay from 0% ConFAV penetration to 100% ConFAVs was calculated for each route. The results are shown according to their relevant junction in Table 5-17 below.

Table 5-17: Delays in Priority Junction 1

Ref	Direction of Movement *(Link No: Link Name - Link No: Link Name)*	0% Pen	20% Pen	40% Pen	60% Pen	80% Pen	100% Pen	Change from 0% to 100%Pen
Priority Junction Number 1	1: Priority JCT 1 - 5: Eastway SB@58.2 - 5: Eastway SB@175.1	0.349	0.234	0.180	0.158	0.100	0.001	-100%
	1: Priority JCT 1 - 5: Eastway SB@58.2 - 22: Osborne Rd SB@26.6	0.160	0.203	0.180	0.115	0.096	0.000	-100%
	1: Priority JCT 1 - 21: Osborne Rd NB@204.8 - 5: Eastway SB@175.1	2.102	1.897	1.706	1.524	1.407	1.520	-28%
	1: Priority JCT 1 - 21: Osborne Rd NB@204.8 - 25: Eastway NB@329.0	2.535	2.706	2.720	2.530	1.801	1.869	-26%
	1: Priority JCT 1 - 25: Eastway NB@211.3 - 22: Osborne Rd SB@26.6	2.489	2.768	2.625	2.431	3.279	3.020	21%
	1: Priority JCT 1 - 25: Eastway NB@211.3 - 25: Eastway NB@329.0	0.359	0.436	0.514	0.525	0.346	0.146	-59%

Within priority junction 1, it was observed that 5 out of the 6 movements recorded a reduction in the average delay of all vehicles. Northbound traffic on Eastway turning right unto Osborne Road saw a fluctuation throughout the simulations, with the highest recorded delay at 80% ConFAV penetration.

It should be noted that all movements had very low average delays with the highest recorded being 3.279 seconds at 80% penetration and 3.020 seconds at 100% penetration.

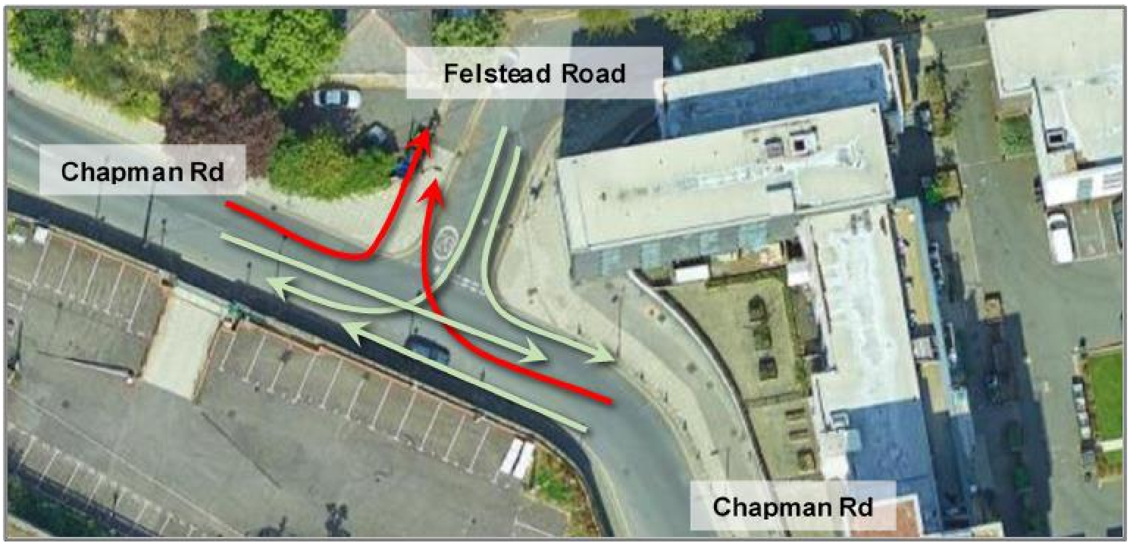
Table 5-18: Delays in Priority Junction 2

Ref	Direction of Movement *(Link No: Link Name - Link No: Link Name)*	0% Pen	20% Pen	40% Pen	60% Pen	80% Pen	100% Pen	Change from 0% to 100%Pen
Priority Junction Number 2	2: Priority JCT 2 - 30: Berkshire SB@133.0 - 30: Berkshire SB@187.1	0.090	0.128	0.093	0.063	0.028	0.008	-91%
	2: Priority JCT 2 - 30: Berkshire SB@133.0 - 37: Felstead Road WB@20.5	2.637	0.393	1.100	1.101	0.441	0.441	-83%
	2: Priority JCT 2 - 36: Felstead Road EB@188.5 - 30: Berkshire SB@187.1	0.704	0.882	0.735	0.760	0.771	0.766	9%
	2: Priority JCT 2 - 36: Felstead Road EB@188.5 - 69: Berkshire NB@74.8	0.446	0.775	0.713	0.752	0.581	0.608	36%
	2: Priority JCT 2 - 69: Berkshire NB@20.7 - 37: Felstead Road WB@20.5	0.147	0.140	0.082	0.081	0.048	0.002	-99%
	2: Priority JCT 2 - 69: Berkshire NB@20.7 - 69: Berkshire NB@74.8	0.154	0.156	0.143	0.117	0.066	0.025	-84%

Within priority junction 2, it was observed that 4 out of the 6 movements recorded very significant reductions in the average delay of all vehicles. Traffic exiting Felstead experienced a fluctuation throughout the simulations. Traffic turning left onto Berkshire experienced its highest level of delays during 20% ConFAV penetration, recorded average delay rising from 0.446 to 0.775 seconds. Traffic turning right onto Berkshire also had its highest increase during 20% ConFAV penetration, recording 0.704 to 0.766 seconds.

It should be noted that all movements had very low average delays with the highest recorded being 0.766 seconds at 100% penetration.

Table 5-19: Delays in Priority Junction 3



Ref	Direction of Movement *(Link No: Link Name - Link No: Link Name)*	0% Pen	20% Pen	40% Pen	60% Pen	80% Pen	100% Pen	Change from 0% to 100%Pen
Priority Junction Number 3	3: Priority JCT 3 - 1: Chapman Road NB@51.2 - 1: Chapman Road NB@138.3	0.354	0.191	0.218	0.148	0.115	0.107	-70%
	3: Priority JCT 3 - 1: Chapman Road NB@51.2 - 36: Felstead Road EB@54.2	2.517	2.421	2.413	2.246	2.082	2.619	4%
	3: Priority JCT 3 - 37: Felstead Road WB@155.2 - 1: Chapman Road NB@138.3	1.373	0.921	0.557	0.595	0.426	0.146	-89%
	3: Priority JCT 3 - 37: Felstead Road WB@155.2 - 52: Chapman Road SB@108.3	0.151	0.028	0.013	0.023	0.070	0.060	-60%
	3: Priority JCT 3 - 52: Chapman Road SB@18.2 - 36: Felstead Road EB@54.2	0.159	0.149	0.134	0.111	0.169	0.194	22%
	3: Priority JCT 3 - 52: Chapman Road SB@18.2 - 52: Chapman Road SB@108.3	0.423	0.378	0.302	0.250	0.168	0.102	-76%

Within priority junction 3, it was observed that 4 out of the 6 movements recorded very significant reductions in the average delay of all vehicles. Traffic turning on to Felstead experienced a fluctuation throughout the simulations with the highest level of delays recorded during 100% ConFAV penetration. Southbound traffic from Chapman Road turning left onto Felstead had a 4% increase amounting to 0.102 seconds at 100% penetration. Northbound traffic turning right onto Felstead Road had a 22% increase amounting to 0.035 seconds.

It should be noted that all movements had very low average delays with the highest recorded being 2.619 seconds at 100% penetration.

Table 5-20: Delays in Signal-Controlled Junction

Ref	Direction of Movement *(Link No: Link Name - Link No: Link Name)*	0% Pen	20% Pen	40% Pen	60% Pen	80% Pen	100% Pen	Change from 0% to 100%Pen
Signal-Controlled Junction	5: Signal Controlled - 10: Wick Road EB@17.4 - 25: Eastway NB@35.0	0.218	0.309	0.212	0.211	0.206	0.098	-55%
	5: Signal Controlled - 13: Wick Road EB@17.2 - 42: Chapman Road SB@33.7	15.680	14.830	13.911	13.209	12.525	11.617	-26%
	5: Signal Controlled - 127: Chapman Road NB@4.1 - 25: Eastway NB@35.0	13.576	13.790	11.961	14.356	13.742	12.447	-8%
	5: Signal Controlled - 127: Chapman Road NB@4.1 - 44: Wick Road NB@50.7	13.661	13.160	13.308	13.143	12.500	11.863	-13%
	5: Signal Controlled - 10012: Eastway NB@7.6 - 42: Chapman Road SB@33.7	18.118	17.436	18.167	17.977	17.632	17.415	-4%
	5: Signal Controlled - 10012: Eastway SB @7.6 - 44: Wick Road WB@50.7	1.338	1.121	0.917	0.703	0.388	0.182	-86%

Within the signal-controlled junction, it was observed that all 6 movements recorded reductions in the average delay of all vehicles. Eastbound traffic on Wick Road turning left onto Eastway say extremely low delay. This is the route that has a permanent green at the junction, which would explain delays being less than 1 second. Southbound traffic on Eastway turning left onto Chapman Road had a significant reduction in delay dropping from 1.338 seconds at 0% penetration to 0.182 seconds at 100% penetration. The other routes ranged between 11.617 and 18.118 seconds and had reductions ranging between 4% to 26% at 100% penetration from 0%.

Table 5-21: Delays in Roundabout

Ref	Direction of Movement *(Link No: Link Name - Link No: Link Name)*	0% Pen	20% Pen	40% Pen	60% Pen	80% Pen	100% Pen	Change from 0% to 100%Pen
Roundabout	4: Roundabout - 1: Chapman Road NB@145.0 - 38: Trowbridge Rd EB@31.4	2.041	1.800	1.353	1.131	0.845	0.864	-58%
	4: Roundabout - 1: Chapman Road NB@145.0 - 43: Chapman Road NB@26.3	2.329	2.038	1.909	1.774	1.377	1.162	-50%
	4: Roundabout - 1: Chapman Road NB@145.0 - 52: Chapman Road SB@11.6	1.901	1.774	1.047	0.721	0.583	0.450	-76%
	4: Roundabout - 8: Trowbridge Rd WB@14.3 - 38: Trowbridge Rd EB@31.4	0.000	0.000	0.000	0.000	0.000	0.000	0
	4: Roundabout - 8: Trowbridge Rd WB@14.3 - 43: Chapman Road NB@26.3	4.013	2.249	1.573	2.949	2.325	1.876	-53%
	4: Roundabout - 8: Trowbridge Rd WB@14.3 - 52: Chapman Road SB@11.6	3.906	1.716	1.547	0.463	0.234	0.062	-98%
	4: Roundabout - 42: Chapman Road SB@46.4 - 38: Trowbridge Rd EB@31.4	2.446	1.762	1.568	1.480	1.451	1.301	-47%
	4: Roundabout - 42: Chapman Road SB@46.4 - 43: Chapman Road NB@26.3	1.779	1.485	1.404	1.352	1.411	1.121	-37%
	4: Roundabout - 42: Chapman Road SB@46.4 - 52: Chapman Road SB@11.6	2.113	1.785	1.587	1.368	1.192	1.027	-51%

Within the roundabout, it was observed that 8 out of 9 movements recorded reductions in the average delay of all vehicles (when comparing 0% ConFAV penetration to 100% ConFAV penetration) ranging between 47% to 98%. Southbound traffic from Trowbridge Road that enter the roundabout to do a U-turn experienced zero (0) delays throughout all 6 simulations. It should be noted that all movements had very low average delays with the highest recorded being 4.013 seconds at 0% penetration.

A summary of all the movements and their changes is shown in the table below.

Ref	Direction of Movement *(Link No: Link Name - Link No: Link Name)*	0% Pen	20% Pen	40% Pen	60% Pen	80% Pen	100% Pen	Change from 0% to 100%Pen
Priority Junction Number 1	1: Priority JCT 1 - 5: Eastway SB@58.2 - 5: Eastway SB@175.1	0.349	0.234	0.180	0.158	0.100	0.001	-100%
	1: Priority JCT 1 - 5: Eastway SB@58.2 - 22: Osborne Rd SB@26.6	0.160	0.203	0.180	0.115	0.096	0.000	-100%
	1: Priority JCT 1 - 21: Osborne Rd NB@204.8 - 5: Eastway SB@175.1	2.102	1.897	1.706	1.524	1.407	1.520	-28%
	1: Priority JCT 1 - 21: Osborne Rd NB@204.8 - 25: Eastway NB@329.0	2.535	2.706	2.720	2.530	1.801	1.869	-26%
	1: Priority JCT 1 - 25: Eastway NB@211.3 - 22: Osborne Rd SB@26.6	2.489	2.768	2.625	2.431	3.279	3.020	21%
	1: Priority JCT 1 - 25: Eastway NB@211.3 - 25: Eastway NB@329.0	0.359	0.436	0.514	0.525	0.346	0.146	-59%
Priority Junction Number 2	2: Priority JCT 2 - 30: Berkshire SB@133.0 - 30: Berkshire SB@187.1	0.090	0.128	0.093	0.063	0.028	0.008	-91%
	2: Priority JCT 2 - 30: Berkshire SB@133.0 - 37: Felstead Road WB@20.5	2.637	0.393	1.100	1.101	0.441	0.441	-83%
	2: Priority JCT 2 - 36: Felstead Road EB@188.5 - 30: Berkshire SB@187.1	0.704	0.882	0.735	0.760	0.771	0.766	9%
	2: Priority JCT 2 - 36: Felstead Road EB@188.5 - 69: Berkshire NB@74.8	0.446	0.775	0.713	0.752	0.581	0.608	36%
	2: Priority JCT 2 - 69: Berkshire NB@20.7 - 37: Felstead Road WB@20.5	0.147	0.140	0.082	0.081	0.048	0.002	-99%
	2: Priority JCT 2 - 69: Berkshire NB@20.7 - 69: Berkshire NB@74.8	0.154	0.156	0.143	0.117	0.066	0.025	-84%
Priority Junction Number 3	3: Priority JCT 3 - 1: Chapman Road NB@51.2 - 1: Chapman Road NB@138.3	0.354	0.191	0.218	0.148	0.115	0.107	-70%
	3: Priority JCT 3 - 1: Chapman Road NB@51.2 - 36: Felstead Road EB@54.2	2.517	2.421	2.413	2.246	2.082	2.619	4%
	3: Priority JCT 3 - 37: Felstead Road WB@155.2 - 1: Chapman Road NB@138.3	1.373	0.921	0.557	0.595	0.426	0.146	-89%
	3: Priority JCT 3 - 37: Felstead Road WB@155.2 - 52: Chapman Road SB@108.3	0.151	0.028	0.013	0.023	0.070	0.060	-60%
	3: Priority JCT 3 - 52: Chapman Road SB@18.2 - 36: Felstead Road EB@54.2	0.159	0.149	0.134	0.111	0.169	0.194	22%

Ref	Direction of Movement *(Link No: Link Name - Link No: Link Name)*	0% Pen	20% Pen	40% Pen	60% Pen	80% Pen	100% Pen	Change from 0% to 100%Pen
	3: Priority JCT 3 - 52: Chapman Road SB@18.2 - 52: Chapman Road SB@108.3	0.423	0.378	0.302	0.250	0.168	0.102	-76%
Roundabout	4: Roundabout - 1: Chapman Road NB@145.0 - 38: Trowbridge Rd EB@31.4	2.041	1.800	1.353	1.131	0.845	0.864	-58%
	4: Roundabout - 1: Chapman Road NB@145.0 - 43: Chapman Road NB@26.3	2.329	2.038	1.909	1.774	1.377	1.162	-50%
	4: Roundabout - 1: Chapman Road NB@145.0 - 52: Chapman Road SB@11.6	1.901	1.774	1.047	0.721	0.583	0.450	-76%
	4: Roundabout - 8: Trowbridge Rd WB@14.3 - 38: Trowbridge Rd EB@31.4	0.000	0.000	0.000	0.000	0.000	0.000	0
	4: Roundabout - 8: Trowbridge Rd WB@14.3 - 43: Chapman Road NB@26.3	4.013	2.249	1.573	2.949	2.325	1.876	-53%
	4: Roundabout - 8: Trowbridge Rd WB@14.3 - 52: Chapman Road SB@11.6	3.906	1.716	1.547	0.463	0.234	0.062	-98%
	4: Roundabout - 42: Chapman Road SB@46.4 - 38: Trowbridge Rd EB@31.4	2.446	1.762	1.568	1.480	1.451	1.301	-47%
	4: Roundabout - 42: Chapman Road SB@46.4 - 43: Chapman Road NB@26.3	1.779	1.485	1.404	1.352	1.411	1.121	-37%
	4: Roundabout - 42: Chapman Road SB@46.4 - 52: Chapman Road SB@11.6	2.113	1.785	1.587	1.368	1.192	1.027	-51%
Signal-Controlled Junction	5: Signal Controlled - 10: Wick Road EB@17.4 - 25: Eastway NB@35.0	0.218	0.309	0.212	0.211	0.206	0.098	-55%
	5: Signal Controlled - 13: Wick Road EB@17.2 - 42: Chapman Road SB@33.7	15.680	14.830	13.911	13.209	12.525	11.617	-26%
	5: Signal Controlled - 127: Chapman Road NB@4.1 - 25: Eastway NB@35.0	13.576	13.790	11.961	14.356	13.742	12.447	-8%
	5: Signal Controlled - 127: Chapman Road NB@4.1 - 44: Chapman Road NB@50.7	13.661	13.160	13.308	13.143	12.500	11.863	-13%
	5: Signal Controlled - 10012: Eastway NB@7.6 - 42: Chapman Road SB@33.7	18.118	17.436	18.167	17.977	17.632	17.415	-4%
	5: Signal Controlled - 10012: Eastway SB @7.6 - 44: Wick Road WB@50.7	1.338	1.121	0.917	0.703	0.388	0.182	-86%

As described in section 3.7.2 of this report, the level of service (LOS) of different routes within the network was determined whether or not the junction was signal-controlled. The parameters used for LOS in this network is shown in Table 5-22 below.

Table 5-22: LOS parameters for signal-controlled junction

	LOS_A	LOS_B	LOS_C	LOS_D	LOS_E	LOS_F
Signal Controlled - Time Lost	Loss time < 10 seconds or no volume	>10s to 20s	>20s to 35s	>35s to 55s	>55s to 80s	>80s
Non-Signal Controlled - Time Lost	Loss time < 10 seconds or no volume	>10s to 15s	>15s to 25s	>25s to 35s	>35s to 50s	>50s

The LOS was calculated for all movements within the network and compared at 0% Penetration with 100% ConFAV penetration. It was observed that while few movements recorded increase in average delay, the analysed junctions within the network were still operating at a level of service of ‘A’. The signal-controlled junction had a level of service of ‘B’ on 4 out of the 6 route choices, which included traffic travelling to and from Chapman Road.

A breakdown of all the movements and their calculated levels of service is shown in Table 5-23 below.

Table 5-23: LOS parameters for signal-controlled junction

Ref	Direction of Movement *(Link No: Link Name - Link No: Link Name)*	Change from 0% Pen to 100% Pen	LOS at 0% Pen	LOS at 100% Pen
Priority Junction Number 1	1: Priority JCT 1 - 5: Eastway SB@58.2 - 5: Eastway SB@175.1	-100%	A	A
	1: Priority JCT 1 - 5: Eastway SB@58.2 - 22: Osborne Rd SB@26.6	-100%	A	A
	1: Priority JCT 1 - 21: Osborne Rd NB@204.8 - 5: Eastway SB@175.1	-28%	A	A
	1: Priority JCT 1 - 21: Osborne Rd NB@204.8 - 25: Eastway NB@329.0	-26%	A	A
	1: Priority JCT 1 - 25: Eastway NB@211.3 - 22: Osborne Rd SB@26.6	21%	A	A
	1: Priority JCT 1 - 25: Eastway NB@211.3 - 25: Eastway NB@329.0	-59%	A	A
Priority Junction Number 2	2: Priority JCT 2 - 30: Berkshire SB@133.0 - 30: Berkshire SB@187.1	-91%	A	A
	2: Priority JCT 2 - 30: Berkshire SB@133.0 - 37: Felstead Road WB@20.5	-83%	A	A
	2: Priority JCT 2 - 36: Felstead Road EB@188.5 - 30: Berkshire SB@187.1	9%	A	A
	2: Priority JCT 2 - 36: Felstead Road EB@188.5 - 69: Berkshire NB@74.8	36%	A	A
	2: Priority JCT 2 - 69: Berkshire NB@20.7 - 37: Felstead Road WB@20.5	-99%	A	A
	2: Priority JCT 2 - 69: Berkshire NB@20.7 - 69: Berkshire NB@74.8	-84%	A	A
Priority Junction Number 3	3: Priority JCT 3 - 1: Chapman Road NB@51.2 - 1: Chapman Road NB@138.3	-70%	A	A
	3: Priority JCT 3 - 1: Chapman Road NB@51.2 - 36: Felstead Road EB@54.2	4%	A	A
	3: Priority JCT 3 - 37: Felstead Road WB@155.2 - 1: Chapman Road NB@138.3	-89%	A	A
	3: Priority JCT 3 - 37: Felstead Road WB@155.2 - 52: Chapman Road SB@108.3	-60%	A	A
	3: Priority JCT 3 - 52: Chapman Road SB@18.2 - 36: Felstead Road EB@54.2	22%	A	A
	3: Priority JCT 3 - 52: Chapman Road SB@18.2 - 52: Chapman Road SB@108.3	-76%	A	A
Roundabout	4: Roundabout - 1: Chapman Road NB@145.0 - 38: Trowbridge Rd EB@31.4	-58%	A	A
	4: Roundabout - 1: Chapman Road NB@145.0 - 43: Chapman Road NB@26.3	-50%	A	A
	4: Roundabout - 1: Chapman Road NB@145.0 - 52: Chapman Road SB@11.6	-76%	A	A
	4: Roundabout - 8: Trowbridge Rd WB@14.3 - 38: Trowbridge Rd EB@31.4	0%	A	A
	4: Roundabout - 8: Trowbridge Rd WB@14.3 - 43: Chapman Road NB@26.3	-53%	A	A

Ref	Direction of Movement *(Link No: Link Name - Link No: Link Name)*	Change from 0% Pen to 100% Pen	LOS at 0% Pen	LOS at 100% Pen
	4: Roundabout - 8: Trowbridge Rd WB@14.3 - 52: Chapman Road SB@11.6	-98%	A	A
	4: Roundabout - 42: Chapman Road SB@46.4 - 38: Trowbridge Rd EB@31.4	-47%	A	A
	4: Roundabout - 42: Chapman Road SB@46.4 - 43: Chapman Road NB@26.3	-37%	A	A
	4: Roundabout - 42: Chapman Road SB@46.4 - 52: Chapman Road SB@11.6	-51%	A	A
Signal-Controlled Junction	5: Signal Controlled - 10: Wick Road EB@17.4 - 25: Eastway NB@35.0	-55%	A	A
	5: Signal Controlled - 13: Wick Road EB@17.2 - 42: Chapman Road SB@33.7	-26%	B	B
	5: Signal Controlled - 127: Chapman Road NB@4.1 - 25: Eastway NB@35.0	-8%	B	B
	5: Signal Controlled - 127: Chapman Road NB@4.1 - 44: Wick Road NB@50.7	-13%	B	B
	5: Signal Controlled - 10012: Eastway NB@7.6 - 42: Chapman Road SB@33.7	-4%	B	B
	5: Signal Controlled - 10012: Eastway SB @7.6 - 44: Wick Road WB@50.7	-86%	A	A

5.4.2 *Safety Performance*

A Surrogate Safety Assessment was carried out according to Section 3.5, by analysing the number of potential conflicts recording along the vehicle trajectories exported from the simulation. The resulting number of serious conflicts and non-serious conflicts for each studied junction within the network are shown in the sections below.

Priority Junctions

The results from the surrogate safety assessment carried out within the three priority junctions are shown in Table 5-24 to Table 5-26 below. For each penetration level, the number of conflicts and the number of vehicles in the area during the simulation are displayed.

Table 5-24: Conflicts in Priority Junction 1

Severity	0% Pen		20% Pen		40% Pen		60% Pen		80% Pen		100% Pen		Change from 0% to 100%Pen
	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	
TTC = 3	35	1530	39	1529	45	1530	34	1532	29	1531	29	1533	-17%
TTC = 2	21		25		28		25		20		19		-10%

Table 5-25: Conflicts in Priority Junction 2

Severity	0% Pen		20% Pen		40% Pen		60% Pen		80% Pen		100% Pen		Change from 0% to 100%Pen
	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	
TTC = 3	2	657	4	656	5	656	7	658	3	658	3	658	+ 50%
TTC = 2	2		3		4		3		2		2		0%

Table 5-26: Conflicts in Priority Junction 3

Severity	0% Pen		20% Pen		40% Pen		60% Pen		80% Pen		100% Pen		Change from 0% to 100%Pen
	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	
TTC = 3	9	1555	20	1555	20	1555	26	1555	27	1555	39	1555	+ 333%
TTC = 2	4		13		14		18		16		25		+ 525 %

Taking a closer look at the results for each of the 3 junctions (locations shown in Figure 5-27 below), it was observed that each behaved differently with the introduction of ConFAVs to the network.

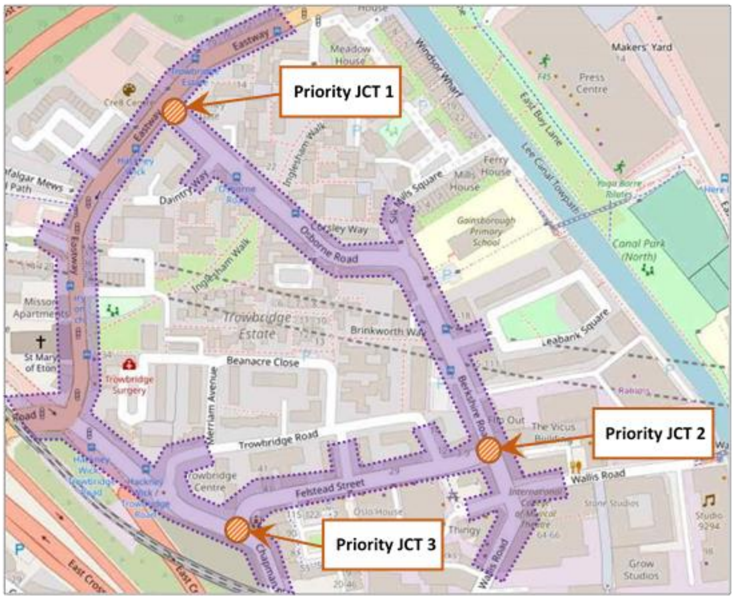


Figure 5-27: Serious VS Non-Serious Conflicts within the Priority Junction

An examination of the number of conflicts within Priority Junction 1 will immediately show a small decrease in numbers between 0% and 100% ConFAV penetration (-17% for TTC = 3 and -10% for TTC=2). To get a wider picture of the impact on the junction itself, it was noted that the number of vehicles passing through it during the 2-hour simulation ranged between 1529 and 1539 during each ConFAV penetration level. When this was compared to the number of recorded conflicts within the stipulated TTC thresholds, it was observed that conflicts ranged between 1% to 3% of the total number of vehicles.

Priority Junction 2 provides different results depending on the TTC threshold value when comparing 0% to 100% ConFAV network penetration. When the TTC threshold is equal to 3 there was 50% increase and when TTC is equal to 2 there was no change. Once again, to put things into perspective, the number of vehicles passing through the junction during the 2-hour simulation was recorded and observed to range between 656 and 658 during each ConFAV penetration level. When this was compared to the number of recorded conflicts within the stipulated TTC thresholds, it was observed that conflicts ranged between 0.3% and 1.1% of the total number of vehicles.

Investigating Priority Junction 3 shows a very significant increase in the number of conflicts for both TTC threshold values when comparing 0% to 100% ConFAV network penetration. The number of vehicles passing through the junction during the 2-hour simulation was observed to be 1555 during each ConFAV penetration level, and when this was compared to the number of recorded conflicts within the stipulated TTC thresholds, it was observed that conflicts ranged between 0.3% and 2.5% of the total number of vehicles.

The changes in conflict across the three junctions are compared in Figure 5-28 to Figure 5-29 below.

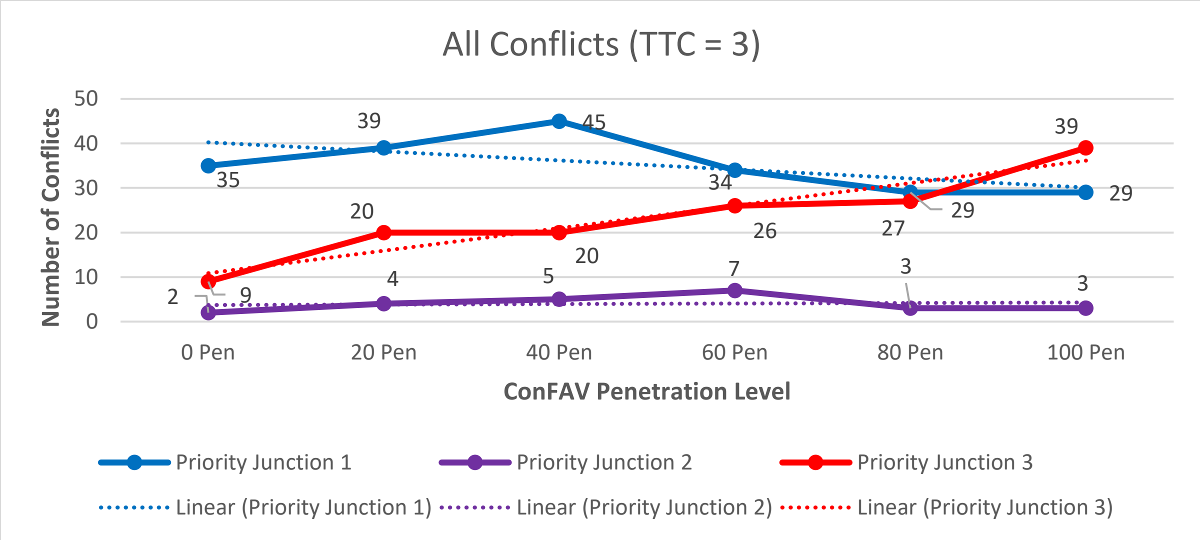


Figure 5-28 Changes in Number of Potential Conflicts within the Priority Junctions

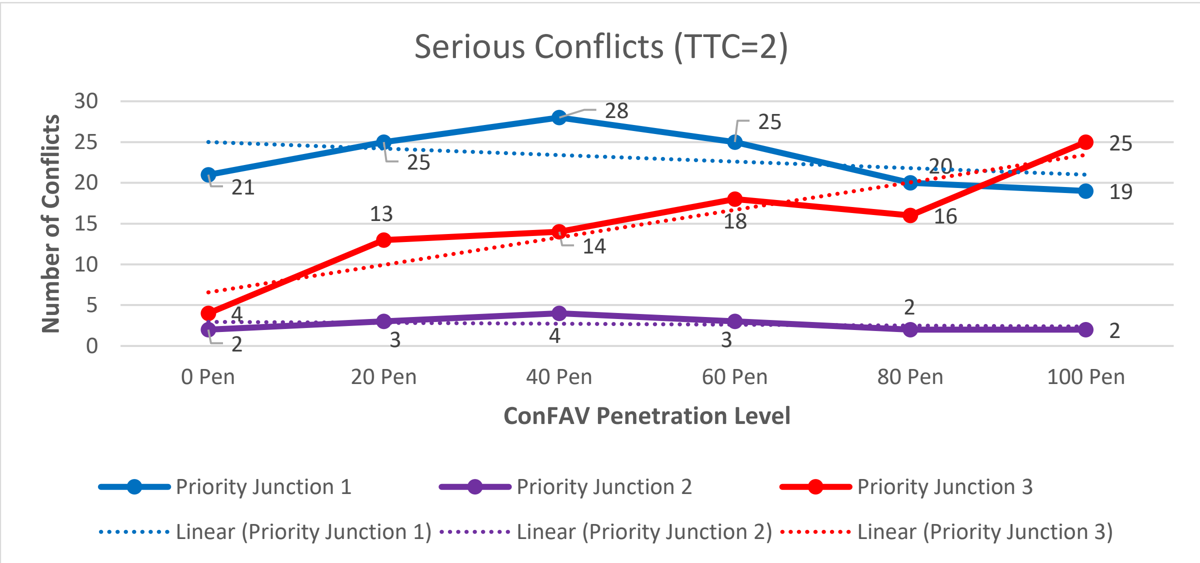


Figure 5-29 Changes in Number of Potentially Serious Conflicts within the Priority Junctions

<u>*Signal-Controlled Junction*</u>

The results from the surrogate safety assessment carried out within the signal-controlled junction are shown in Table 5-27 below.

Table 5-27: Conflicts in Signal-Controlled Junction

Severity	0% Pen		20% Pen		40% Pen		60% Pen		80% Pen		100% Pen		Change from 0% to 100%Pen
	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	
TTC = 3	255	2737	269	2737	316	2737	415	2737	478	2737	489	2738	+ 92%
TTC = 2	97		127		148		207		267		262		+ 170 %

In stark comparison to the priority junctions examined earlier, it was observed that the number of conflicts recorded in this signal-controlled junction were quite high when the TTC threshold is set to 3. This gradually increased with the number of ConFAVs entering the network, until the number of conflicts nearly doubled at 100% penetration (an increase of 92%).

A similar, but steeper trend was observed in the number of conflicts when the TTC threshold was set to 2. A continuous steep rise was observed up to 80% ConFAV penetration, after which it almost levelled out at 100%. The increase from 0% to 100% penetration recorded an increase of 170% more potentially serious conflicts within the junction.

The number of vehicles passing through the junction during the 2-hour simulation ranged between 2737 and 2738 during each ConFAV penetration level. When this was compared to the number of recorded conflicts within the stipulated TTC thresholds, it was observed that conflicts ranged between 9% to 18% and 4% to 10% of the total number of vehicles when the TTC threshold is set to 3 and 2 respectively.

The trends observed within the junction are shown in Figure 5-30 below.

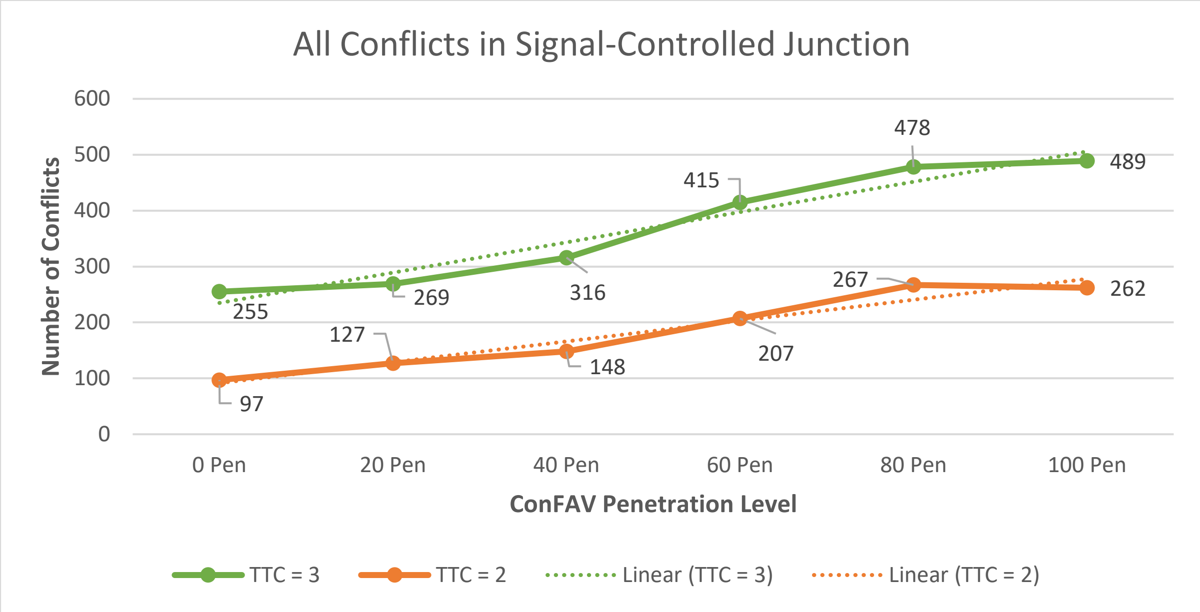


Figure 5-30 Changes in Number of Potentially Serious Conflicts within the Priority Junctions

Roundabout

The results from the surrogate safety assessment carried out within the roundabout are plotted on the graph in Table 5-28 below.

Table 5-28: Conflicts in Roundabout

Severity	0% Pen		20% Pen		40% Pen		60% Pen		80% Pen		100% Pen		Change from 0% to 100%Pen
	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	No. of Conf.	No. of Vehs.	
TTC = 3	272	1743	281	1744	331	1743	382	1746	415	1746	398	1746	+ 46%
TTC = 2	79		123		159		186		230		217		+ 175 %

Similar to the signal-controlled junction, the number of conflicts recorded in this roundabout was quite high when the TTC threshold is set to 3. This gradually increased with the number of ConFAVs entering the network, until the number of conflicts increased by 46%.

A much steeper trend was observed in the number of conflicts when the TTC threshold was set to 2. A continuous steep rise was observed up to 80% ConFAV penetration, after which it slightly dropped at 100%. The increase from 0% to 100% penetration recorded an increase of 175% more potentially serious conflicts within the junction.

The number of vehicles passing through the junction during the 2-hour simulation ranged between 1743 and 1746 during each ConFAV penetration level. When this was compared to the number of recorded conflicts within the stipulated TTC thresholds, it was observed that conflicts ranged between 16% to 24% and 5% to 13% of the total number of vehicles when the TTC threshold is set to 3 and 2 respectively.

The trends observed within the junction are shown in Figure 5-31 below.

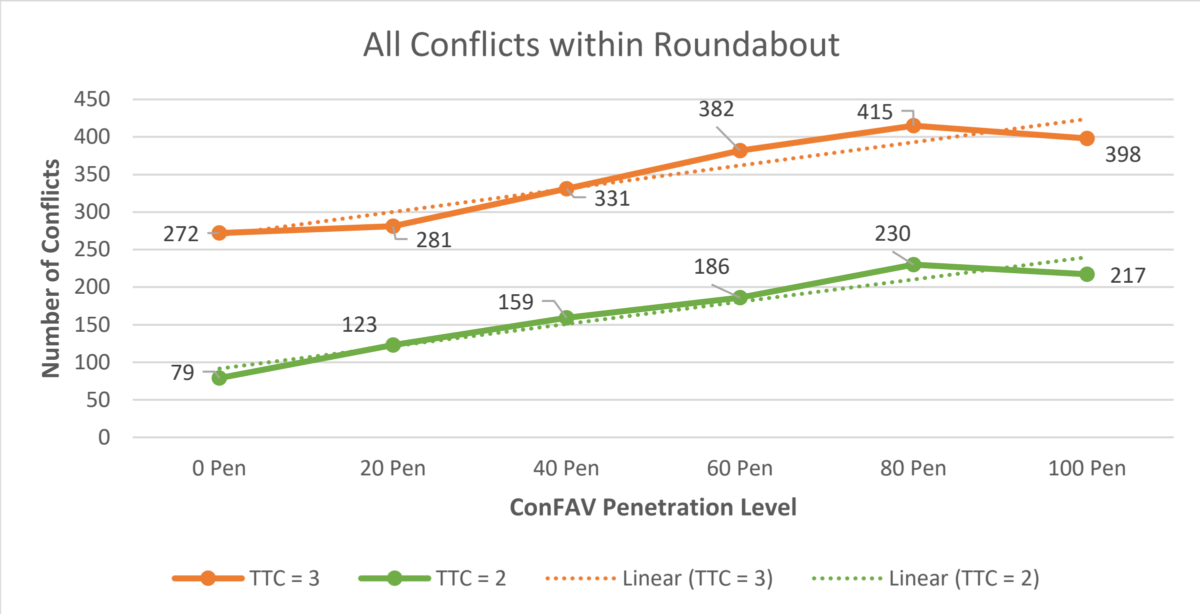


Figure 5-31 Changes in Number of Potentially Serious Conflicts within the Priority Junctions

5.5 Findings and Analysis for Site B: Westfield

5.5.1 Congestion Performance: Vehicle Delay & Network LOS

The average vehicle delay along all eighteen (18) routes identified within network was compared for the six (6) ConFAV penetration levels, and the percentage change in the recorded average delay from 0% ConFAV penetration to 100% ConFAVs was calculated for each route and shown in Table 5-29 below.

Table 5-29 Average Vehicle Delays & Vehicles in Network Comparison

		0% ConFAV Penetration		20% ConFAV Penetration		40% ConFAV Penetration		60% ConFAV Penetration		80% ConFAV Penetration		100% ConFAV Penetration		Change from 0% ConFAV to 100% ConFAV Penetration
Ref	Direction of Movement *(Link No: Link Name - Link No: Link Name)*	Avg Delay	Avg VEHs	Avg Delay	Avg VEHs	Avg Delay	Avg VEHs	Avg Delay	Avg VEHs	Avg Delay	Avg VEHs	Avg Delay	Avg VEHs	
1	1: INTL SB - 7: Waterden RD WB	58	13	57	12	54	12	53	13	48	14	48	15	-17%
2	1: INTL SB - 12: OLYMP NB	30	1	69	2	43	2	32	2	34	1	46	1	52%
3	1: INTL SB - 14: WA EB	31	2	30	2	38	2	25	1	18	1	0	0	-100%
4	8: Waterden RD EB - 2: INTL NB	20	12	17	11	20	13	16	13	14	13	16	13	-19%
5	8: Waterden RD EB - 4: ROUND H EB	27	71	26	72	25	71	25	70	24	72	22	72	-16%
6	8: Waterden RD EB - 12: OLYMP NB	20	17	19	17	20	17	18	17	17	17	16	17	-19%
7	8: Waterden RD EB - 14: WA EB	25	87	25	89	24	88	23	88	23	86	23	87	-8%
8	10: ROUND H WB - 7: Waterden RD WB	51	52	50	53	50	54	47	55	46	56	44	54	-13%
9	10: ROUND H WB - 12: OLYMP NB	55	8	50	6	51	6	44	8	45	8	47	8	-13%
10	10: ROUND H WB - 14: WA EB	32	65	31	65	30	65	31	63	29	61	28	63	-12%
11	11: OLYMP SB - 2: INTL NB	35	2	33	2	17	2	28	3	24	3	37	2	7%
12	11: OLYMP SB - 4: ROUND H EB	34	16	33	15	33	16	32	16	32	16	30	16	-11%
13	11: OLYMP SB - 7: Waterden RD WB	27	12	27	12	27	12	26	12	27	12	25	12	-8%
14	11: OLYMP SB - 14: WA EB	9	0	27	1	25	1	9	0	0	0	0	0	-100%
15	13: WA WB - 2: INTL NB	48	7	40	8	36	7	38	6	29	6	33	7	-30%
16	13: WA WB - 4: ROUND H EB	49	43	48	42	45	43	43	44	44	44	43	43	-13%
17	13: WA WB - 7: Waterden RD WB	9	18	9	17	8	17	8	18	8	17	8	17	-17%
18	13: WA WB - 12: OLYMP NB	5	1	7	3	9	3	12	2	10	2	6	3	31%

An overall reduction in average delays was seen throughout the network, ranging from 8% to 30% less delays at 100% ConFAV penetration when compared to 0% ConFAVs.

It was noted that the routes highlighted in red had a very low number of vehicles on the link (less than or equal to 3), which meant that the sample size was too low to produce conclusive and significant results. It was concluded that the simulation produced really low vehicle numbers along these routes (shown in the diagram below labelled with the reference numbers shown in Table 5-29 above) within the 15 minutes intervals due to the typically low volume of vehicles making these routing choices while navigating this section of the network.

The results for these 5 movements were inconclusive and thus was not considered in the analysis.

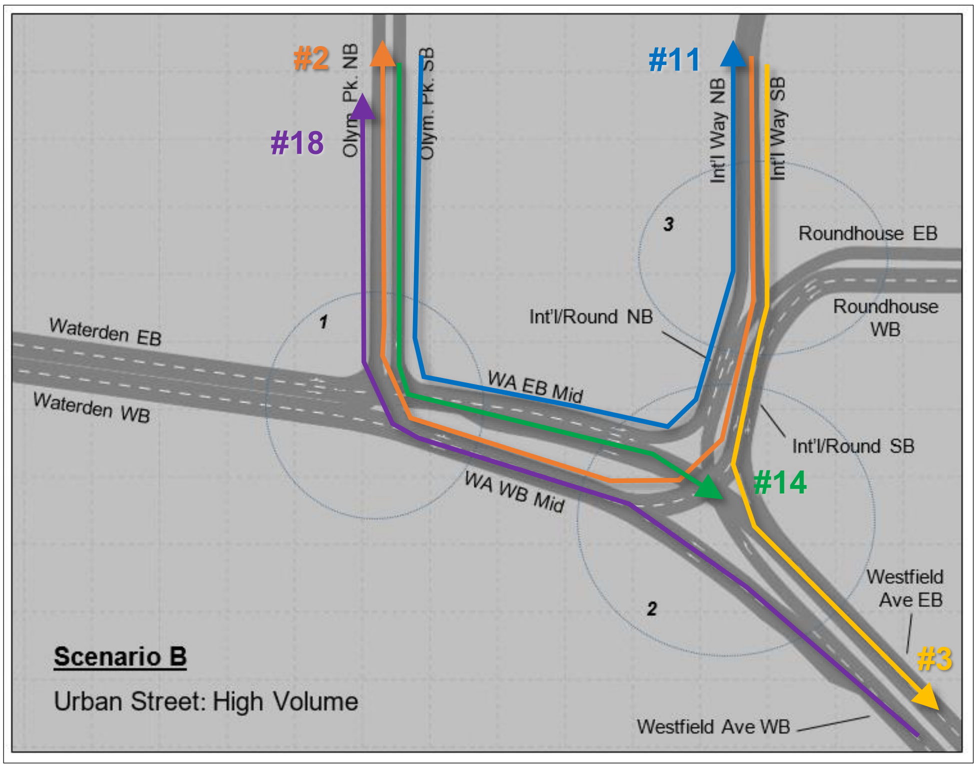


Figure 5-32: Layout of links in road network

As described in 3.7.2 of this report, the level of service (LOS) of different routes within the network was determined using the Signal-controlled parameters. The parameters used for LOS in this network is shown in Table 5-30 below.

Table 5-30: LOS parameters for signal-controlled junction

LOS	A	B	C	D	E	F
Time Lost	Loss time < 10 seconds or no volume	>10s to 20s	>20s to 35s	>35s to 55s	>55s to 80s	>80s

The LOS was calculated for all movements within the network except for the five routes that had vehicles numbers below the threshold for conclusive results. It was observed that changes in time lost was so low that 11 out of the 13 movements examined had no changes in their level of service. After 40% ConFAV penetration, vehicles traveling southbound from International way to go westbound on Waterden Road had an improvement in the route's LOS. The same was observed after 80% ConFAV penetration for vehicles travelling westbound on Westfield Avenue turning right at junction 2 then continuing northbound along International Way.

Table 5-31: Calculated LOS for each Direction of Movement

REF	DIRECTION OF MOVEMENT	Calculated LOS for ConFAV Penetration Levels					
		0%	20%	40%	60%	80%	100%
1	**1: INTL SB - 7: Waterden RD WB**	**E**	**E**	**D**	**D**	**D**	**D**
4	8: Waterden RD EB - 2: INTL NB	B	B	B	B	B	B
5	8: Waterden RD EB - 4: ROUND H EB	C	C	C	C	C	C
6	8: Waterden RD EB - 12: OLYMP NB	B	B	B	B	B	B
7	8: Waterden RD EB - 14: WA EB	C	C	C	C	C	C
8	10: ROUND H WB - 7: Waterden RD WB	D	D	D	D	D	D
9	10: ROUND H WB - 12: OLYMP NB	D	D	D	D	D	D
10	10: ROUND H WB - 14: WA EB	C	C	C	C	C	C
12	11: OLYMP SB - 4: ROUND H EB	C	C	C	C	C	C
13	11: OLYMP SB - 7: Waterden RD WB	C	C	C	C	C	C
15	**13: WA WB - 2: INTL NB**	**D**	**D**	**D**	**D**	**C**	**C**
16	13: WA WB - 4: ROUND H EB	D	D	D	D	D	D
17	13: WA WB - 7: Waterden RD WB	A	A	A	A	A	A

It can be concluded that automation within this isolated network did not provide a major benefit in the reduction of delays. The average delay of vehicles for each movement at different penetration levels are shown in the tables below.

Vehicle Delays at 0% ConFAV Penetration

Direction	Total Avg. VEH Delay over 2 hours	Total Avg. VEH Delay every 15 mins	LOS for Signal-controlled
1-1: INTL SB@205.8-7: Waterden RD WB@74.3	466	58	E
1-1: INTL SB@205.8-12: OLYMP NB@85.6	242	30	C
1-1: INTL SB@205.8-14: WA EB@81.7	245	31	C
1-8: Waterden RD EB@50.4-2: INTL NB@50.0	156	20	B
1-8: Waterden RD EB@50.4-4: ROUND H EB@30.2	213	27	C
1-8: Waterden RD EB@50.4-12: OLYMP NB@85.6	159	20	B
1-8: Waterden RD EB@50.4-14: WA EB@81.7	201	25	C

Direction	Total Avg. VEH Delay over 2 hours	Total Avg. VEH Delay every 15 mins	LOS for Signal-controlled
1-10: ROUND H WB@6.6-7: Waterden RD WB@74.3	408	51	D
1-10: ROUND H WB@6.6-12: OLYMP NB@85.6	438	55	D
1-10: ROUND H WB@6.6-14: WA EB@81.7	255	32	C
1-11: OLYMP SB@18.7-2: INTL NB@50.0	277	35	C
1-11: OLYMP SB@18.7-4: ROUND H EB@30.2	270	34	C
1-11: OLYMP SB@18.7-7: Waterden RD WB@74.3	220	27	C
1-11: OLYMP SB@18.7-14: WA EB@81.7	73	9	A
1-13: WA WB@17.6-2: INTL NB@50.0	381	48	D
1-13: WA WB@17.6-4: ROUND H EB@30.2	395	49	D
1-13: WA WB@17.6-7: Waterden RD WB@74.3	74	9	A
1-13: WA WB@17.6-12: OLYMP NB@85.6	37	5	A

Vehicle Delays at 20% ConFAV Penetration

Direction	Total Avg. VEH Delay over 2 hours	Total Avg. VEH Delay every 15 mins	LOS for Signal-controlled
1-1: INTL SB@205.8-7: Waterden RD WB@74.3	452	57	E
1-1: INTL SB@205.8-12: OLYMP NB@85.6	548	69	E
1-1: INTL SB@205.8-14: WA EB@81.7	243	30	C
1-8: Waterden RD EB@50.4-2: INTL NB@50.0	136	17	B
1-8: Waterden RD EB@50.4-4: ROUND H EB@30.2	211	26	C
1-8: Waterden RD EB@50.4-12: OLYMP NB@85.6	154	19	B
1-8: Waterden RD EB@50.4-14: WA EB@81.7	201	25	C
1-10: ROUND H WB@6.6-7: Waterden RD WB@74.3	400	50	D
1-10: ROUND H WB@6.6-12: OLYMP NB@85.6	399	50	D
1-10: ROUND H WB@6.6-14: WA EB@81.7	250	31	C
1-11: OLYMP SB@18.7-2: INTL NB@50.0	263	33	C
1-11: OLYMP SB@18.7-4: ROUND H EB@30.2	267	33	C
1-11: OLYMP SB@18.7-7: Waterden RD WB@74.3	220	27	C
1-11: OLYMP SB@18.7-14: WA EB@81.7	214	27	C
1-13: WA WB@17.6-2: INTL NB@50.0	319	40	D
1-13: WA WB@17.6-4: ROUND H EB@30.2	386	48	D
1-13: WA WB@17.6-7: Waterden RD WB@74.3	69	9	A
1-13: WA WB@17.6-12: OLYMP NB@85.6	55	7	A

Vehicle Delays at 40% ConFAV Penetration

Vehicle Movement/Route	Total Avg. VEH Delay over 2 hours	Total Avg. VEH Delay every 15 mins	LOS for Signal-controlled
1-1: INTL SB@205.8-7: Waterden RD WB@74.3	430	54	D
1-1: INTL SB@205.8-12: OLYMP NB@85.6	340	43	D
1-1: INTL SB@205.8-14: WA EB@81.7	303	38	D

Vehicle Movement/Route	Total Avg. VEH Delay over 2 hours	Total Avg. VEH Delay every 15 mins	LOS for Signal-controlled
1-8: Waterden RD EB@50.4-2: INTL NB@50.0	162	20	C
1-8: Waterden RD EB@50.4-4: ROUND H EB@30.2	197	25	C
1-8: Waterden RD EB@50.4-12: OLYMP NB@85.6	156	20	B
1-8: Waterden RD EB@50.4-14: WA EB@81.7	193	24	C
1-10: ROUND H WB@6.6-7: Waterden RD WB@74.3	398	50	D
1-10: ROUND H WB@6.6-12: OLYMP NB@85.6	406	51	D
1-10: ROUND H WB@6.6-14: WA EB@81.7	243	30	C
1-11: OLYMP SB@18.7-2: INTL NB@50.0	134	17	B
1-11: OLYMP SB@18.7-4: ROUND H EB@30.2	265	33	C
1-11: OLYMP SB@18.7-7: Waterden RD WB@74.3	216	27	C
1-11: OLYMP SB@18.7-14: WA EB@81.7	198	25	C
1-13: WA WB@17.6-2: INTL NB@50.0	289	36	D
1-13: WA WB@17.6-4: ROUND H EB@30.2	360	45	D
1-13: WA WB@17.6-7: Waterden RD WB@74.3	62	8	A
1-13: WA WB@17.6-12: OLYMP NB@85.6	69	9	A

Vehicle Delays at 60% ConFAV Penetration

Vehicle Movement/Route	Total Avg. VEH Delay over 2 hours	Total Avg. VEH Delay every 15 mins	LOS for Signal-controlled
1-1: INTL SB@205.8-7: Waterden RD WB@74.3	426	53	D
1-1: INTL SB@205.8-12: OLYMP NB@85.6	258	32	C
1-1: INTL SB@205.8-14: WA EB@81.7	200	25	C
1-8: Waterden RD EB@50.4-2: INTL NB@50.0	128	16	B
1-8: Waterden RD EB@50.4-4: ROUND H EB@30.2	197	25	C
1-8: Waterden RD EB@50.4-12: OLYMP NB@85.6	146	18	B
1-8: Waterden RD EB@50.4-14: WA EB@81.7	186	23	C
1-10: ROUND H WB@6.6-7: Waterden RD WB@74.3	373	47	D
1-10: ROUND H WB@6.6-12: OLYMP NB@85.6	351	44	D
1-10: ROUND H WB@6.6-14: WA EB@81.7	249	31	C
1-11: OLYMP SB@18.7-2: INTL NB@50.0	224	28	C
1-11: OLYMP SB@18.7-4: ROUND H EB@30.2	260	32	C
1-11: OLYMP SB@18.7-7: Waterden RD WB@74.3	207	26	C
1-11: OLYMP SB@18.7-14: WA EB@81.7	74	9	A
1-13: WA WB@17.6-2: INTL NB@50.0	300	38	D
1-13: WA WB@17.6-4: ROUND H EB@30.2	345	43	D
1-13: WA WB@17.6-7: Waterden RD WB@74.3	60	8	A
1-13: WA WB@17.6-12: OLYMP NB@85.6	96	12	B

Vehicle Delays at 80% ConFAV Penetration

Vehicle Movement/Route	Total Avg. VEH Delay over 2 hours	Total Avg. VEH Delay every 15 mins	LOS for Signal-controlled
1-1: INTL SB@205.8-7: Waterden RD WB@74.3	385	48	D
1-1: INTL SB@205.8-12: OLYMP NB@85.6	270	34	C
1-1: INTL SB@205.8-14: WA EB@81.7	144	18	B
1-8: Waterden RD EB@50.4-2: INTL NB@50.0	115	14	B
1-8: Waterden RD EB@50.4-4: ROUND H EB@30.2	190	24	C
1-8: Waterden RD EB@50.4-12: OLYMP NB@85.6	136	17	B
1-8: Waterden RD EB@50.4-14: WA EB@81.7	188	23	C
1-10: ROUND H WB@6.6-7: Waterden RD WB@74.3	369	46	D
1-10: ROUND H WB@6.6-12: OLYMP NB@85.6	356	45	D
1-10: ROUND H WB@6.6-14: WA EB@81.7	234	29	C
1-11: OLYMP SB@18.7-2: INTL NB@50.0	194	24	C
1-11: OLYMP SB@18.7-4: ROUND H EB@30.2	259	32	C
1-11: OLYMP SB@18.7-7: Waterden RD WB@74.3	212	27	C
1-11: OLYMP SB@18.7-14: WA EB@81.7	0	0	A
1-13: WA WB@17.6-2: INTL NB@50.0	235	29	C
1-13: WA WB@17.6-4: ROUND H EB@30.2	352	44	D
1-13: WA WB@17.6-7: Waterden RD WB@74.3	62	8	A
1-13: WA WB@17.6-12: OLYMP NB@85.6	80	10	A

Vehicle Delays at 100% ConFAV Penetration

Vehicle Movement/Route	Total Avg. VEH Delay over 2 hours	Total Avg. VEH Delay every 15 mins	LOS for Signal-controlled
1-1: INTL SB@205.8-7: Waterden RD WB@74.3	385	48	D
1-1: INTL SB@205.8-12: OLYMP NB@85.6	369	46	D
1-1: INTL SB@205.8-14: WA EB@81.7	0	0	A
1-8: Waterden RD EB@50.4-2: INTL NB@50.0	126	16	B
1-8: Waterden RD EB@50.4-4: ROUND H EB@30.2	180	22	C
1-8: Waterden RD EB@50.4-12: OLYMP NB@85.6	129	16	B
1-8: Waterden RD EB@50.4-14: WA EB@81.7	184	23	C
1-10: ROUND H WB@6.6-7: Waterden RD WB@74.3	355	44	D
1-10: ROUND H WB@6.6-12: OLYMP NB@85.6	379	47	D
1-10: ROUND H WB@6.6-14: WA EB@81.7	225	28	C
1-11: OLYMP SB@18.7-2: INTL NB@50.0	297	37	D
1-11: OLYMP SB@18.7-4: ROUND H EB@30.2	240	30	C
1-11: OLYMP SB@18.7-7: Waterden RD WB@74.3	203	25	C
1-11: OLYMP SB@18.7-14: WA EB@81.7	0	0	A
1-13: WA WB@17.6-2: INTL NB@50.0	267	33	C
1-13: WA WB@17.6-4: ROUND H EB@30.2	343	43	D
1-13: WA WB@17.6-7: Waterden RD WB@74.3	62	8	A
1-13: WA WB@17.6-12: OLYMP NB@85.6	49	6	A

5.5.2 Safety Performance

The results from the surrogate safety assessment carried out within the isolated network are shown in Table 5-32 below.

Table 5-32: Conflicts in Signal-Controlled Junction

Severity	0% Pen No. of Conf.	20% Pen No. of Conf.	40% Pen No. of Conf.	60% Pen No. of Conf.	80% Pen No. of Conf.	100% Pen No. of Conf.	Change from 0% to 100%Pen
TTC = 3	1210	1570	2976	3983	5417	6845	+ 466%
TTC = 2	662	792	1630	1734	2252	2804	+ 324%

It was observed that the number of conflicts recorded in this network of three signal-controlled junctions were quite high for a TTC threshold of 3. This vastly increased with the number of ConFAVs entering the network, until the number of conflicts more than quadrupled (an increase of 466%) at 100% ConFAV penetration.

A similar, but steeper trend was observed in the number of conflicts when the TTC threshold was set to 2. There was a continuous steep rise as the number of ConFAVs within the network rose from a 0% to 100% penetration rate. This number jumped by 324% when the records at 0% ConFAVs penetration was compared to 100%.

The number of vehicles passing through the network during the 2-hour simulation ranged between 3420 and 3437 during each ConFAV penetration level. However, this was not compared to the number of conflicts, because each vehicle entering the network had to pass through 2 or more junctions drastically increasing the likelihood of being in conflict with another. The number of lanes entering the junction from one link were also not consistent ranging from 1 to 3, which also increased a vehicle's potential to be in conflict with another.

The trends observed within the isolated network are shown in Figure 5-33 below.

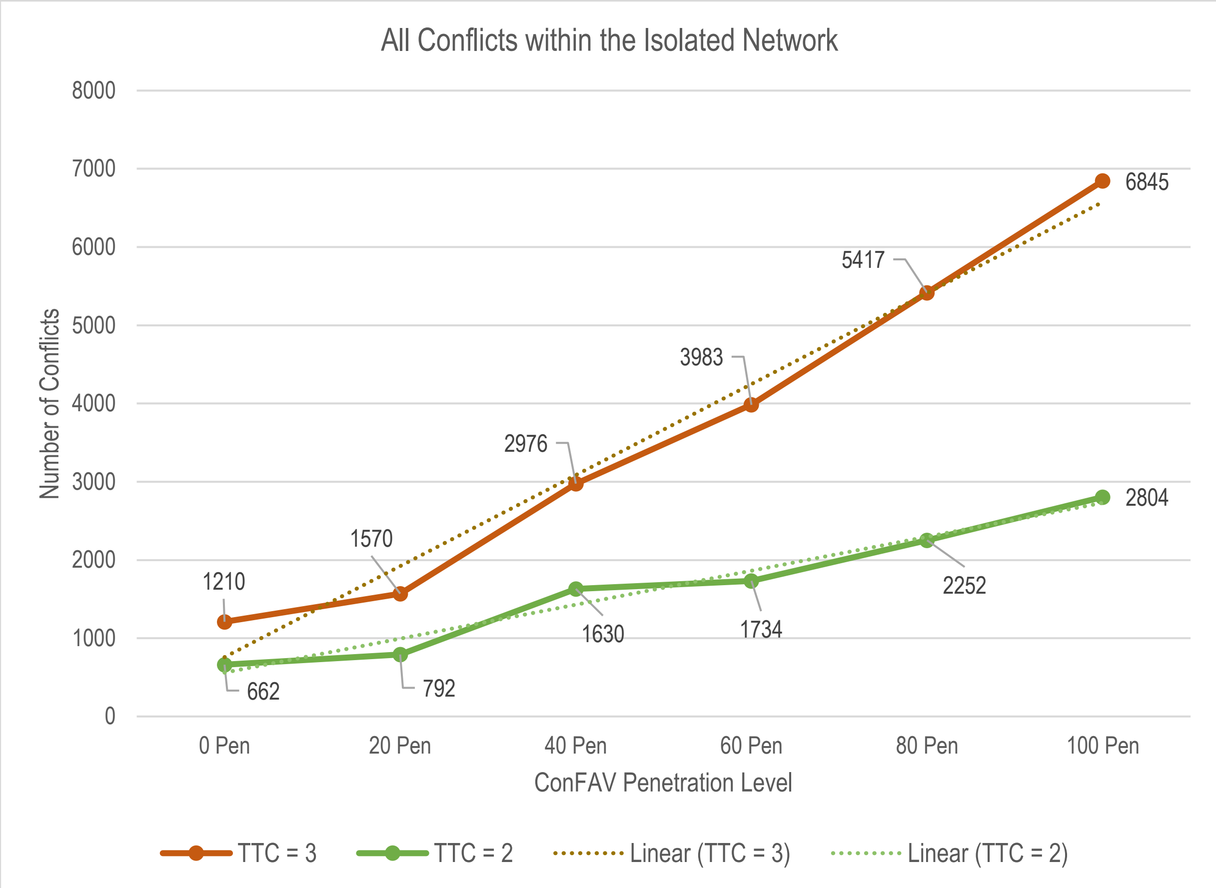


Figure 5-33 Changes in the number of Conflicts within the Isolated Network

5.6 Discussion & Conclusions

5.6.1 Site A: Hackney Wick

It was observed that there was an overall reduction in the delay within the network as the penetration levels of ConFAVs increased, despite the junction type.

Priority junctions within the experiment saw delay of vehicles turning onto Felstead Road from Chapman Road as well as those turning out of Felstead Road onto Berkshire Road. Felstead Road is positioned at the bottom of the network near two main vehicle input/exit points. Route preferences of vehicles passing through these two junctions creates a smaller percentage of users turning onto Felstead Road from Chapman Road, possibly making it difficult to pass between the platoons of vehicles entering the junction. The greater the percentage of ConFAVs within the network, the more platoons will form, thus the increase in delay faced by those attempting to enter or leave Felstead Road. Nonetheless, the increases in the average delay are so minor that the user may not notice a difference. At 100% ConFAV penetration the average delay varies between 0.608 and 0.766 seconds for those leaving Felstead onto Berkshire Road, and between 0.194 and 2.619 seconds for those leaving Chapman Road onto Felstead Road.

The priority junction observed at the north-eastern end of the network saw an increase in delays for right turns from the main road onto the side road, of 2.489 seconds to 3.020 seconds for 0% and 100% ConFAV penetration rates respectively. This movement was affected by three others as it passed through 3 conflict zones before getting to the destination link.

Movements within the roundabout had little to no delays, as this ranged between 0 seconds to 4.013 seconds at 0% ConFAV penetration, and between 0 seconds and 1.876 seconds at 100% Penetration. This is in contrast to the priority junctions as all arms of the roundabout were made equal, as each vehicle entering the roundabout needed to give way to the vehicle on the right regardless of the arm they are on.

Unlike the others, the signal-controlled junction experienced noticeable delays. The level of service (LOS) within the priority junctions and the roundabout were all classed as “A” throughout the simulation, however 4 out of the 6 movements within the signal-controlled junction earned an LOS class of “B”. Similar to the roundabout, despite the delays being higher in this junction, the average vehicle delay dropped for all movements within the junction at 100% ConFAV penetration when compared to 0% penetration.

Safety

In contrast to the performance in delays, it was noted that there was a slight decrease in recorded conflicts within Priority junction 1, but the other 4 junctions saw increasing ranging from +50% to +525%.

The most important point to note that while these increases (or decrease) was evident, the number of vehicles within the network was much higher than the number of potential conflicts recorded. It was observed that conflicts ranged between 0.3% and 3% of the total number of vehicles that travel through the priority junctions, where these total number of vehicles ranged between 656 and 1555.

The junction type that had the highest number of vehicles travelling through was the signal-controlled junction that ranged between 2737 and 2738 for each simulation. The roundabout had the second highest ranging between 1743 and 1746 vehicles per simulation.

The signal-controlled junction was the most congested but was experienced the second greatest percentage of conflicts per vehicle, which ranged between 9% to 18% and 4% to 10% of the total number of vehicles when the TTC threshold is set to 3 and 2 respectively. This junction experienced a 92% increase in conflicts at 100% ConFAV penetration when compared to 0%, when the TTC threshold was set to 3. At a TTC threshold of 2, this junction had a 170% increase in potentially serious conflicts at 100% ConFAV penetration when compared to 0%.

While the roundabout experienced no increase in delays on any of its routes, but it had the highest percentage of conflicts per vehicle ranging from 16% to 24% and 5% to 13% of the total number of vehicles when the TTC threshold is set to 3 and 2 respectively. This junction experienced a 46% increase in conflicts at 100% ConFAV penetration when compared to 0%, when the TTC threshold was set to 3. At a TTC threshold of 2, this junction had a 175% increase in potentially serious conflicts at 100% ConFAV penetration when compared to 0%.

A high-level comparison of the resulting conflicts is shown in Figure 5-34 to Figure 5-35 below for each of the junction types within the network.

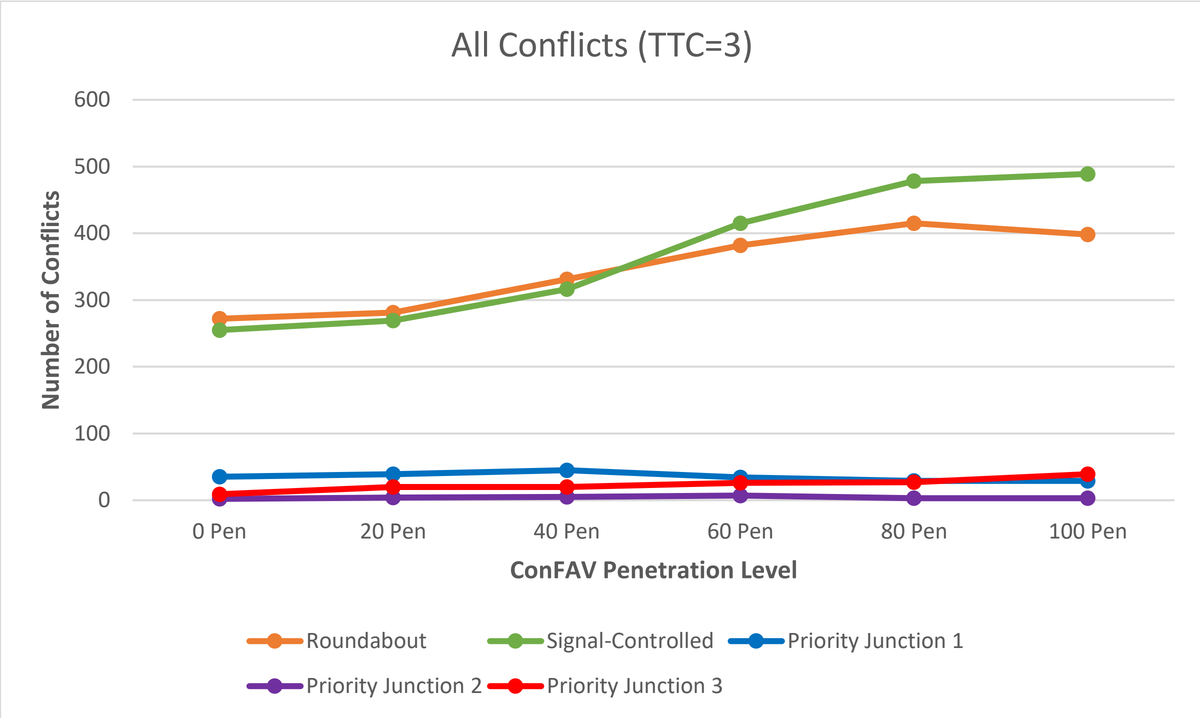


Figure 5-34 All conflicts recorded within the Network

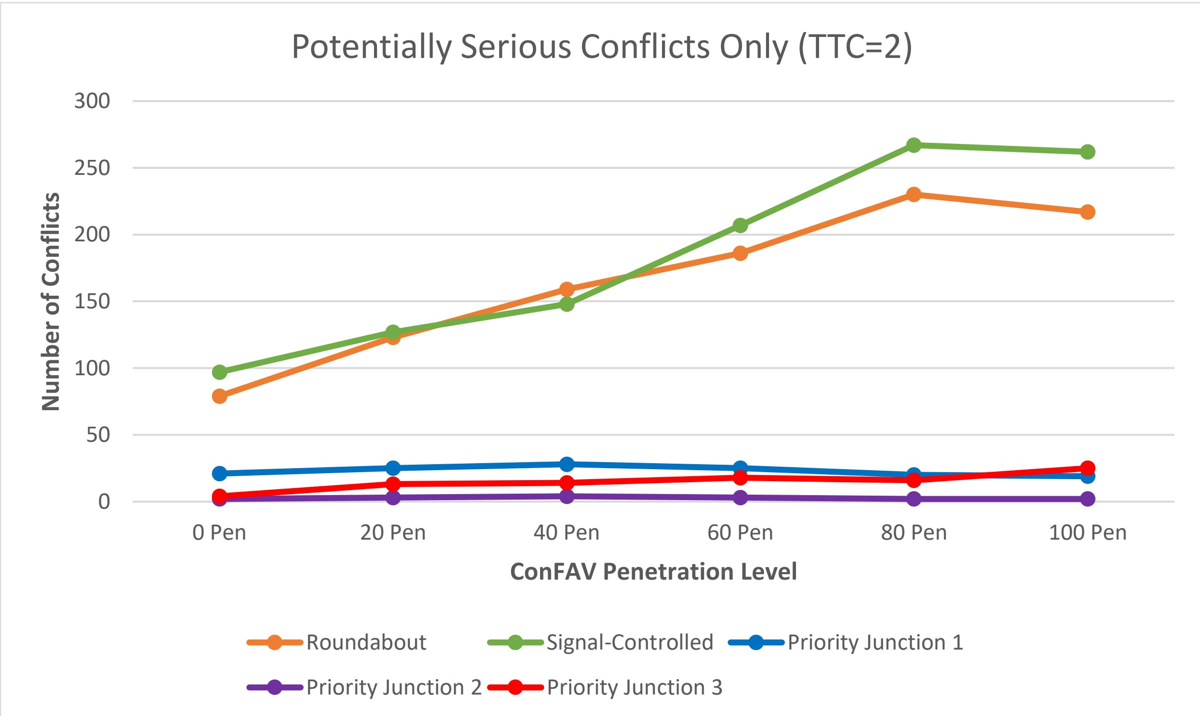


Figure 5-35 All potentially serious conflicts recorded within the network

As the majority of potential conflicts were classified as rear-end conflicts, and these rose drastically with the introduction of ConFAVs, it can be concluded that this increase was as a result of the close following distances of the platoons of ConFAVs within the network. The greater number of platoons travelling closely behind each other, the greater number of potential rear end conflicts recorded within the network.

5.6.2 Site B: Westfield

It was observed that there was an overall reduction of delay within the isolated network. Five out of the 18 routes within the network had extremely low levels of vehicles and so could not provide statistically conclusive results. When the other 13 routes are analysed, all routes experienced a reduction in delay ranging between 8% and 30% at 100% ConFAV penetration when compared to 0% ConFAVs.

These reductions did not translate into an improvement of the LOS for all of the routes, as the average delays still fell within the defined limits of the LOS category at 0% penetration and 100% penetration. Two movements out of the 13 routes had small improvements in their LOS category with one changing from category “D” to category “C”, and another from Category “E” to Category “D” at 80% and 40% FAV penetration respectively.

Safety

Similar to the behaviour of the signal-controlled junction in Site A, this isolated network of three signal-controlled junctions experienced a steady increase in potential conflicts as the number of ConFAVs entering the network increased. There was a 466% increase in conflicts at 100% ConFAV penetration when compared to 0%, when the TTC threshold was set to 3. At a TTC threshold of 2, this junction had a 324% increase in potentially serious conflicts at 100% ConFAV penetration when compared to 0%.

A comparison of the number of conflicts to the number of vehicles in the network per simulation was not carried out, as each vehicle was required to traverse 2 or more junctions per route choice, which exposed it to a greater risk of conflict.

Similarly, to Site A, the majority of potential conflicts were classified as rear-end conflicts, which drastically increased with the introduction of ConFAVs to the network. Thus, it can be concluded that this increase was as a result of the close following distances of the platoons of ConFAVs within the network. The greater number of platoons travelling closely behind each other, the greater number of potential rear end conflicts recorded within the network.

5.6.3 Conclusions

Two conclusions were drawn after reviewing the results of this chapter:

- While the introduction of ConFAVs within the network had consistent improvement in delays, these changes were so small there were no significant impact on the level of service of the links.
- The greater number of ConFAVs within the network meant a greater number of platoons of vehicles travelling closely behind each other, which in turn results in a greater number of potential rear end conflicts recorded within the network.

5.7 Chapter Summary

The case study explored the impact of ConFAVs operating within 2 small, isolated networks within the Queen Elizabeth Olympic Park Area of London. The two locations were chosen based on the classification of users, and the transportation needs that they represented. The sites were:

- <u>Residential</u>: Hackney Wick
- <u>Commercial</u>: Westfield

The network for each site was modelled using the existing geometry of the locations, an estimation of traffic volume using public traffic count data, the same relative flow distribution as previously used in the classification of ConFAV penetration, the CoEXist ConFAV driving behaviour model, and right of way rules (or signal programmes) based on the type of junction.

All junctions within Site A performed well when the average delays are compared against the ConFAV penetration levels, with only a few movements having a total increase of 3 seconds or less. All junctions except 1 priority junction appear to perform poorly when comparing the number of recorded conflicts with the increasing numbers of ConFAVs.

Site B showed little to no improvement in LOS following the introduction of ConFAVs, as the changes in the average delays were too small to change the category of the links. This network also performed extremely poorly in the safety analysis as the number of recorded conflicts increased by as much as 466% at 100% ConFAV penetration when compared to 0%.

It was concluded that increased numbers of ConFAVs within the network could slightly reduce delays, but may have little to no impact on LOS, and greater numbers of ConFAVs mean greater numbers of platoons resulting in larger numbers of rear-end conflicts.

6. CONCLUSION AND RECOMMENDATIONS

This study can be concluded by looking at the answer to the three questions that the research objective set out to achieve. These are detailed below in subsections 6.1 to 6.3.

6.1 How are connected fully autonomous vehicles (ConFAVs) expected to behave within urban road networks?

The potential impact of Connected Fully Autonomous Vehicles (ConFAVs) on the safety and efficiency of road networks was explored using microsimulation software.

A literature review was carried out on the state of the art of driverless technology, to gain an understanding of what is known about the potential driving behaviour of the connected fully autonomous vehicle. The projected operational impacts of these vehicles were researched, as well as what known potential risks could possibly accompany these vehicles during the transition period.

A research methodology was devised using two main software, PTV VISSIM and the SSAM software that collates the data from the trajectories of the vehicles within the VISSIM simulation. The VISSIM model was calibrated and validated using network and user data gathered from site visits as well as credible publications (such as statistics from the Department for Transport).

The ConFAVs' driving behaviours was then tested to determine the most efficient model and the model with the least risk of vehicular conflicts, then using the results of that experiment the vehicles were then assessed within isolated networks once again.

Two published behaviour models (Atkins and CoEXist) were identified, and a third model (Tested Logic) was created, which takes into consideration varying driving behaviours of the ConFAV dependent on whether it is following another of its kind versus a conventional human driver with no data connectivity. The driving behaviours were tested using microsimulation on three types of junctions, designed to UK standards:

- Priority Junction
- Signal-controlled junction
- Roundabout

Rules were defined for each junction type within the simulation software based on the UK road rules and by adjusting the following:

- Vehicle input and route decision data.
- Desired speed distribution.
- Vehicle composition and relative flow.
- Junction right of way rules using conflict zones.
- Signal phases for the signal-controlled junction.

A comparison of the average change in delays experienced across all route movements within each junction type for all three models has highlighted that the Tested Logic behavioural model has performed the best in both the signal-controlled junction and roundabout, while Atkins performed the best within the priority junction. All three models recorded a reduction in delays within the junction, ranging from an average of -28.01% to -66.04%. However, the CoEXist model was the worst performer among the three, with a difference of 0.37 to 3.21 percentage points when compared with the best performing model.

A comparison of the change in the number of serious conflicts recorded across all route movements within each junction type for all three models has highlighted that the CoEXist behavioural model has performed the best in all junction types being the only one to consistently reduce the total number of serious conflicts. The CoEXist model recorded a difference of 7.32 to 48.42 percentage points when compared with the worst performing models.

The highest reduction in serious conflicts was observed within the roundabout, while the least was observed in the signal-controlled junction. The signal-controlled junction was the only one to experience an increase in the number of serious conflicts for the Atkins and Tested Logic behavioural models.

A recommendation was made to use the CoEXist model as the others had a high cost of potentially serious collisions while providing only a very small benefit in the reduction of average delays within the junction.

6.2 What operational impacts can ConFAVs have on the level of service of urban road networks during the transition period (where there is a mix of both conventional and autonomous vehicles) and full automation?

The case study was based in the Queen Elizabeth Olympic Park Area of London and explored the impact of ConFAVs operating within 2 isolated zones: Hackney Wick and Westfield. The zones were chosen based on the classification of users, and the transportation needs that they represented. Hackney Wick was selected because it was predominantly residential and Westfield because of the commercial district and the international train station next to it.

The existing geometry of the locations was used to model the network for each site and published traffic count data was used to estimate the vehicle input volume. Previously discussed relative flow distribution and ConFAV classification was applied to the network models. The tested CoEXist ConFAV driving behaviour model was calibrated to into each network and similar the right of way rules (or signal programmes) were chosen based on the type of junction.

It was observed within Site A that there was an overall improvement of average delays at the studied junctions the more ConFAVs added to the network. There were only a few route choices that experienced a total increase of 3 seconds or less in delays.

At Site B the changes in average delays were too small to change the level of service (LOS) category of the links which produced little to no improvement in LOS following the introduction of ConFAVs.

The case study drew a conclusion that increased numbers of ConFAVs within the network could slightly reduce delays but may have little to no impact on LOS.

6.3 Are there any associated collision risk factors of ConFAVs within urban road networks?

The behaviour model was run using the same case study of two isolated sites based in the Queen Elizabeth Olympic Park Area of London to explore any potential impact of ConFAVs on the safety of the network.

It was observed within Site A all junctions except 1 priority junction appear to perform poorly when comparing the number of recorded conflicts with the increasing numbers of ConFAVs. Site B performed extremely poorly as the number of recorded conflicts increased by as much as 466% at 100% ConFAV penetration when compared to 0% penetration (100% conventional vehicles).

The case study drew a conclusion that increased numbers of ConFAVs within the network greatly increased the numbers of platoons being formed, which resulted in larger numbers of potential rear-end conflicts.

6.4 Research Outputs

The resulting output of this research project canned be summarised in 3 bullet points:

- The final model used to test the case study within this project could be used as a flexible transport planning tool to assess the impact of ConFAV driving behaviour in small, isolated networks where a limited number of variables are needed to link observed changes the parameters being tested.
- Insight was provided on the potential impact of ConFAVs on delay within small, isolated Road Networks, and a conflict data examined to find a link between changes in recorded conflicts and increased numbers of ConFAVs within the network.
- This research made two recommendations based on the observations from the experiments, which are explained in more detail in section 6.5 below.

6.5 Resulting Recommendations

6.5.1 <u>ConFAV Driving Behaviour Model</u>

As the difference between CoEXist and best performing models for average delays is only up to a maximum of **3.21** percentage points, while the difference between CoEXist and the worst performing model for serious conflicts ranges between **7.32** and **48.42** percentage points, it could be said that benefit of a reduction in delays was negligible when compared to the cost of serious conflicts.

Thus, out of the three options, it was recommended that CoEXist be used as the model for ConFAV driving behaviour.

6.5.2 Network Efficiency and Safety

Two observations were made after reviewing the results of the case study:

- In the majority of cases, changes in delay were so small following the introduction of ConFAVs to the network that there were no significant impacts on the level of service of the links examined.
- The greater the number of platoons within the network, the greater the number of potential rear end conflicts. This was a result of the analysis technique being based on time to collision values which are directly influenced by how closely a vehicle is travelling behind the other and was developed based on human drivers with reaction times to consider.

Thus, it is recommended that further research be carried out to investigate how potentially dangerous conflicts can be studied without the results being skewed by the existence platoons.

6.6 Confidence of Simulation Results

Estimates within this study were calculated from sample data to analyse the impact of assumptions made using the PTV VISSIM software. As it is not at all possible to test the assumptions of the ConFAV driving behaviour in large quantities on the road, because enough is not known about its interaction with human drivers (and how safe it would be to mix them into the road network in large quantities), it was not feasible or possible to test assumptions in the real-world to give 100% confidence in the results gathered. As the technology continues to develop, further work is needed to better understand its driving behaviours.

6.7 Future Work

It would be beneficial if further work is done to ascertain if similar results could be achieved through the provision of real-time traffic signal status in all human driven vehicles, allowing the driver to adjust their speeds accordingly. This would reduce the number of start-stop instances in the drive cycle.

To fully realise this potential solution, future research will be required to look at larger networks with more degraded levels of service. The parameters for LOS categorisation used may also need rethinking as a delay of 1 second may have a different impact on platoons of ConFAVs than it would on conventional vehicles traversing the junction.

However, while the potential success of the ConFAV in reducing delay is apparent in some instances in the case study, the number of ConFAVs on the road is highly dependent on customer acceptance and willingness to buy these vehicles. Continuous research into the common concerns of future customers will be key in the implementation of widespread ConFAV uptake.

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APPENDICES

Appendix A. UTMS Society of Japan areas of research

Since the UTMS Society of Japan started in 2012 they have narrowed their research to the following UTMS applications:

- ITCS (Integrated Traffic Control Systems): The key component of advanced traffic management through optimal signal control that is based on real-time information.
- AMIS (Advanced Mobile Information Systems): A data dissemination tool that feeds information from the Traffic Control Centre to the mobile navigation systems found in the vehicle.
- PTPS (Public Transportation Priority Systems): A system designed to give priority to public transport by way of traffic lights and designated lanes.
- MOCS (Mobile Operation Control Systems): An advanced fleet management tool designed to allow for the tracking of vehicles.
- EPMS (Environment Protection Management Systems): A tool designed to monitor air pollution and noise pollution along a route, and then adjust the traffic controls accordingly by limiting traffic flow and providing alternative route guidance.
- DSSS (Driving Safety Support Systems): A tool used to detect other road users including non-motorised users, alerting the driver of their presence.
- HELP (Help system for Emergency Life saving and Public safety): A tool used to reduce the number of fatalities in traffic accidents, by alerting emergency services upon impact or through driver interaction.
- PICS (Pedestrian Information and Communication Systems): A tool used to help the disabled and elderly to navigate intersections through the exchange of data between the RSUs and the pedestrian's device.
- FAST (Fast Emergency Vehicle Pre-emption Systems): A tool used to allow emergency vehicles to get to their destination without being stopped at intersections, while warning other road users along their path.

Appendix B. Guide to SAE Defined Autonomy Levels

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, 2014)

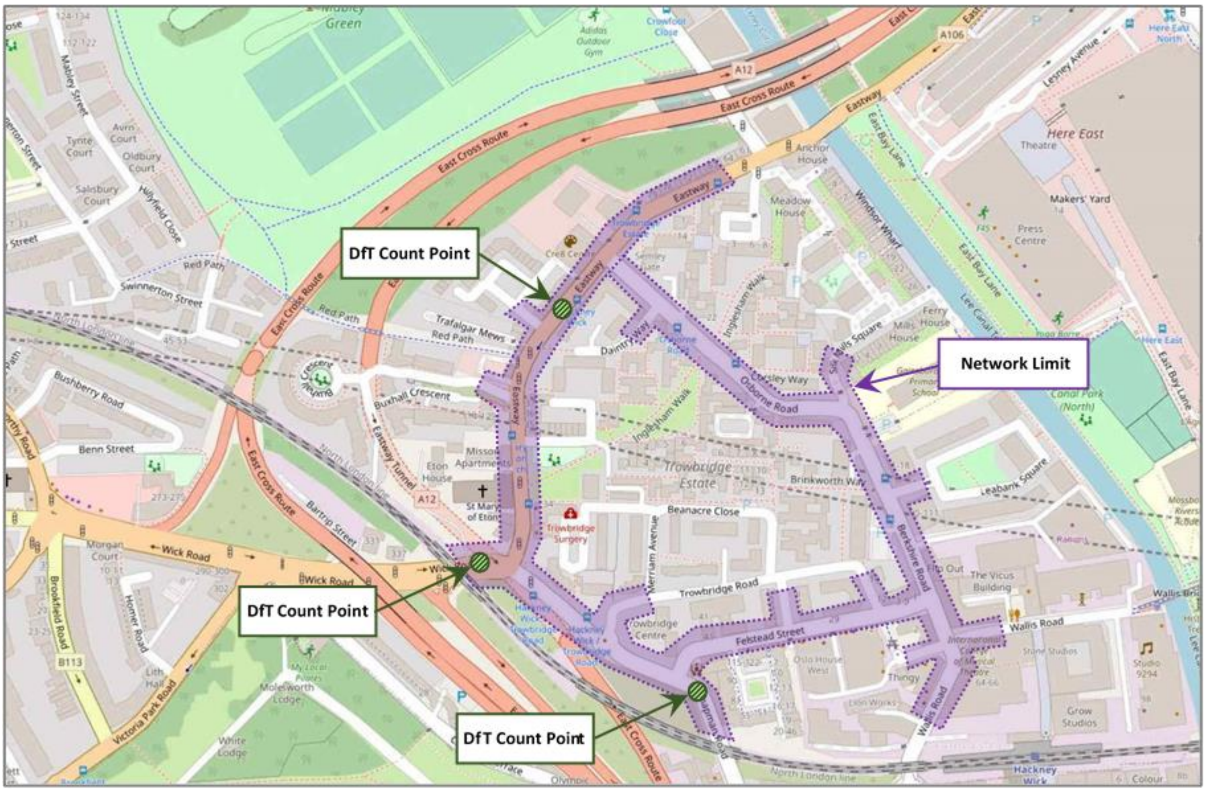
Appendix C. Site A Vehicle Static Route Decisions

The following table shows the static route decisions assigned to all decision points within the Hackney Wick network model.

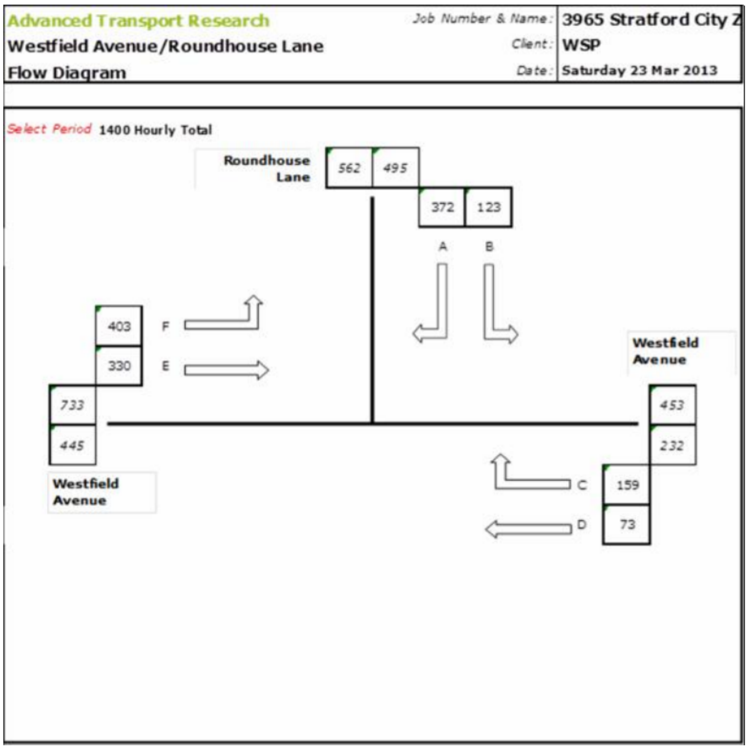
Location Description	Route Decision		
	Left Turn	Through	Right Turn
1. Entry Point 3	---	0.9	0.1
2. Felstead WB x Chapman	0.4	---	0.6
3. Chapman SB Enter Roundabout	0.15	0.8	0.05
4. Entry Point 4	0.050	0.8	0.15
5. Berkshire NB x Felstead Jct	0.1	0.9	---
6. Berkshire NB x Atlas Wharf Jct	---	0.79	0.21
7. Berkshire NB x Leabank Square	---	0.9	0.1
8. Berkshire NB x Osborne Road	---	0.95	0.05
9. Osborne NB x Brinkworth Way	0.1	0.9	---
10. Osborne NB x Daintry Way	0.1	0.9	---
11. Entry Point 1	0.1	0.9	---
12. Eastway NB x Osborne	---	0.9	0.1
13. Daintry NB x Osborne	0.5	---	0.5
14. Osborne SB x Daintry	---	0.9	0.1
15. Osborne NB x Eastway	0.6	---	0.4
16. Brinkworth NB x Osborne	0.5	---	0.5
17. Osborne SB x Brinkworth	---	0.9	0.1
18. Silk Mills x Berkshire	0.5	---	0.5
19. Osborne SB x Silk Mills	0.5	0.95	---
20. Berkshire SB x Leabank	0.1	0.9	---
21. Leabank WB x Berkshire	0.5	---	0.5
22. Berkshire SB x Atlas Wharf	0.21	0.79	---
23. Atlas Wharf WB x Berkshire	0.5	---	0.5
24. Berkshire SB x Felstead	---	0.9	0.1
25. Felstead EB x Berkshire	0.6	---	0.4
26. Prince Ed Dead End x Berkshire	0.4	0.2	0.4
27. Berkshire SB x Wallis	0.30	0.65	0.05
28. Wallis WB x Berkshire	0.45	0.05	0.5

Location Description	Route Decision		
	Left Turn	Through	Right Turn
29. Chapman SB x Felstead	0.2	0.8	---
30. Felstead EB x Gainsborough	0.25	0.75	---
31. Felstead WB x Gainsborough	---	0.8	0.2
32. Gainsborough SB x Felstead	0.5	---	0.5
33. Prince Edward SB x Felstead	0.5	---	0.5
34. Felstead WB x Prince Edward	---	0.8	0.2
35. Felstead EB x Prince Edward	0.2	0.8	---
36. Eastway SB x Shalbourne	---	0.95	0.05
37. Eastway NB x Shalbourne	0.05	0.95	---
38. Shalbourne EB x Eastway	0.5	---	0.5
39. Eastway SB x Buxhall	---	0.94	0.06
40. Eastway NB x Buxhall	0.06	0.94	---
41. Buxhall EB x Eastway	0.5	---	0.5
42. Berkshire NB x School	0.03	0.97	---
43. Berkshire SB x School	---	0.97	0.03
44. School WB x Berkshire	0.5	---	0.5
45. Chapman NB x Eastway	0.29	---	0.71
46. Wick Rd EB x Eastway	---	1	---
47. Eastway SB x Chapman	0.05	0.8	0.15
48. Wick Rd EB x Eastway	0.49	0.02	0.49
49. Chapman NB Enter Roundabout	---	---	1
50. Trowbridge enter roundabout	0.09	0.91	---
51. Entry Point 2	---	0.79	0.21

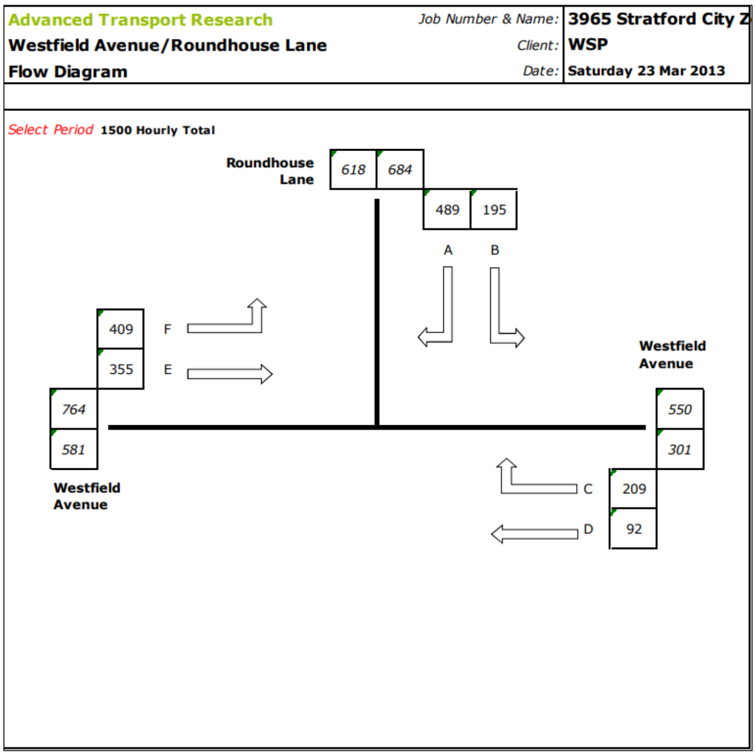
Appendix D. The Department for Transport (DfT) Traffic Volume Count Points within the network limit



Appendix E. Vehicle turning counts at junction of Westfield Avenue and Roundhouse Lane on Saturday 23rd March 2013



Afternoon 14.00 – 15.00 hours



Afternoon 15.00 – 16.00 hours

Appendix F. Average Delay of Vehicles at Site B – Westfield at each ConFAV penetration level

Ref	Direction of Movement (Link No: Link Name - Link No: Link Name)	0% ConFAV Penetration Avg Delay	0% ConFAV Penetration Avg VEHs	20% ConFAV Penetration Avg Delay	20% ConFAV Penetration Avg VEHs	40% ConFAV Penetration Avg Delay	40% ConFAV Penetration Avg VEHs	60% ConFAV Penetration Avg Delay	60% ConFAV Penetration Avg VEHs	80% ConFAV Penetration Avg Delay	80% ConFAV Penetration Avg VEHs	100% ConFAV Penetration Avg Delay	100% ConFAV Penetration Avg VEHs	Change from 0% ConFAV to 100% ConFAV Penetration
1	1: INTL SB - 7: Waterden RD WB	58	13	57	12	54	12	53	13	48	14	48	15	-17%
2	1: INTL SB - 12: OLYMP NB	30	1	69	2	43	2	32	2	34	1	46	1	52%
3	1: INTL SB - 14: WA EB	31	2	30	2	38	2	25	1	18	1	0	0	-100%
4	8: Waterden RD EB - 2: INTL NB	20	12	17	11	20	13	16	13	14	13	16	13	-19%
5	8: Waterden RD EB - 4: ROUND H EB	27	71	26	72	25	71	25	70	24	72	22	72	-16%
6	8: Waterden RD EB - 12: OLYMP NB	20	17	19	17	20	17	18	17	17	17	16	17	-19%
7	8: Waterden RD EB - 14: WA EB	25	87	25	89	24	88	23	88	23	86	23	87	-8%
8	10: ROUND H WB - 7: Waterden RD WB	51	52	50	53	50	54	47	55	46	56	44	54	-13%
9	10: ROUND H WB - 12: OLYMP NB	55	8	50	6	51	6	44	8	45	8	47	8	-13%
10	10: ROUND H WB - 14: WA EB	32	65	31	65	30	65	31	63	29	61	28	63	-12%
11	11: OLYMP SB - 2: INTL NB	35	2	33	2	17	2	28	3	24	3	37	2	7%
12	11: OLYMP SB - 4: ROUND H EB	34	16	33	15	33	16	32	16	32	16	30	16	-11%
13	11: OLYMP SB - 7: Waterden RD WB	27	12	27	12	27	12	26	12	27	12	25	12	-8%
14	11: OLYMP SB - 14: WA EB	9	0	27	1	25	1	9	0	0	0	0	0	-100%
15	13: WA WB - 2: INTL NB	48	7	40	8	36	7	38	6	29	6	33	7	-30%
16	13: WA WB - 4: ROUND H EB	49	43	48	42	45	43	43	44	44	44	43	43	-13%
17	13: WA WB - 7: Waterden RD WB	9	18	9	17	8	17	8	18	8	17	8	17	-17%
18	13: WA WB - 12: OLYMP NB	5	1	7	3	9	3	12	2	10	2	6	3	31%

Appendix G. Conflict Zones within Area A Model – Hackney Wick

LINK1	LINK2	STATUS
25: Eastway NB	10011: chapman to eastway NB	Passive
10009: wick to chapman SB	10011: chapman to eastway NB	Passive
10009: wick to chapman SB	10014: eastway to wick SB	Passive
10011: chapman to eastway NB	10014: eastway to wick SB	Passive
42: Chapman Road SB	10015: eastway to chapman SB	Passive
10009: wick to chapman SB	10015: eastway to chapman SB	Passive
10014: eastway to wick SB	10015: eastway to chapman SB	Passive
52: Chapman Road SB	10018: felstead to chapman LT	Passive
52: Chapman Road SB	10019: felstead to chapman RT	Passive
10018: felstead to chapman LT	10019: felstead to chapman RT	Passive
52: Chapman Road SB	10020: chapman SB to felstead	Passive
21: Osborne Rd NB	10041: daintry to osborne LT	2 waits for 1
21: Osborne Rd NB	10042: daintry to osborne RT	2 waits for 1
22: Osborne Rd SB	10042: daintry to osborne RT	2 waits for 1
10041: daintry to osborne LT	10042: daintry to osborne RT	Passive
21: Osborne Rd NB	10043: Osborne to Daintry NB LT	Passive
21: Osborne Rd NB	10044: osborne to daintry SB RT	2 waits for 1
22: Osborne Rd SB	10044: osborne to daintry SB RT	Passive
10042: daintry to osborne RT	10044: osborne to daintry SB RT	1 waits for 2
10043: Osborne to Daintry NB LT	10044: osborne to daintry SB RT	2 waits for 1
25: Eastway NB	10046: osborne to eastway RT	2 waits for 1
10045: osborne to eastway LT	10046: osborne to eastway RT	Passive
25: Eastway NB	10047: eastway to osborne NB RT	Passive
10046: osborne to eastway RT	10047: eastway to osborne NB RT	1 waits for 2
22: Osborne Rd SB	10048: Eastway to osborne SB LT	1 waits for 2
10047: eastway to osborne NB RT	10048: Eastway to osborne SB LT	1 waits for 2
36: Felstead Road EB	10059: Felstead to Gainsborough EB LT	Passive
36: Felstead Road EB	10060: Felstead to Gainsborough WB RT	2 waits for 1
37: Felstead Road WB	10060: Felstead to Gainsborough WB RT	Passive
10059: Felstead to Gainsborough EB LT	10060: Felstead to Gainsborough WB RT	2 waits for 1
36: Felstead Road EB	10061: Gainsborough to Felstead SB RT	2 waits for 1
37: Felstead Road WB	10061: Gainsborough to Felstead SB RT	2 waits for 1
10060: Felstead to Gainsborough WB RT	10061: Gainsborough to Felstead SB RT	2 waits for 1
36: Felstead Road EB	10062: Gainsborough to Felstead SB LT	2 waits for 1
10061: Gainsborough to Felstead SB RT	10062: Gainsborough to Felstead SB LT	Passive
36: Felstead Road EB	10067: felstead to Edward NB LT	Passive

LINK1	LINK2	STATUS
39: Prince Edward NB	10067: felstead to Edward NB LT	1 waits for 2
36: Felstead Road EB	10070: felstead WB to Edward NB RT	2 waits for 1
37: Felstead Road WB	10070: felstead WB to Edward NB RT	Passive
39: Prince Edward NB	10070: felstead WB to Edward NB RT	2 waits for 1
10067: felstead to Edward NB LT	10070: felstead WB to Edward NB RT	2 waits for 1
36: Felstead Road EB	10073: Edward SB to felstead EB LT	2 waits for 1
36: Felstead Road EB	10074: Edward SB to felstead WB RT	2 waits for 1
37: Felstead Road WB	10074: Edward SB to felstead WB RT	2 waits for 1
10070: felstead WB to Edward NB RT	10074: Edward SB to felstead WB RT	2 waits for 1
10073: Edward SB to felstead EB LT	10074: Edward SB to felstead WB RT	Passive
36: Felstead Road EB	10075: felstead to Berkshire LT	Passive
30: Berkshire SB	10076: felstead to Berkshire RT	2 waits for 1
36: Felstead Road EB	10076: felstead to Berkshire RT	Passive
10075: felstead to Berkshire LT	10076: felstead to Berkshire RT	Passive
30: Berkshire SB	10077: Berkshire SB to felstead RT	Passive
10076: felstead to Berkshire RT	10077: Berkshire SB to felstead RT	1 waits for 2
37: Felstead Road WB	10078: Berkshire NB to felstead LT	Passive
10077: Berkshire SB to felstead RT	10078: Berkshire NB to felstead LT	1 waits for 2
69: Berkshire NB	10075: felstead to Berkshire LT	2 waits for 1
69: Berkshire NB	10076: felstead to Berkshire RT	2 waits for 1
69: Berkshire NB	10077: Berkshire SB to felstead RT	2 waits for 1
69: Berkshire NB	10078: Berkshire NB to felstead LT	Passive
69: Berkshire NB	10079: Edward to Berkshire LT	2 waits for 1
30: Berkshire SB	10096: Wallis Rd WB to Edward	2 waits for 1
65: Prince Edward Rd DeadEnd WB	10096: Wallis Rd WB to Edward	Passive
69: Berkshire NB	10096: Wallis Rd WB to Edward	2 waits for 1
30: Berkshire SB	10097: Edward Rd EB to Wallis	2 waits for 1
69: Berkshire NB	10097: Edward Rd EB to Wallis	2 waits for 1
10079: Edward to Berkshire LT	10097: Edward Rd EB to Wallis	Passive
30: Berkshire SB	10098: Wallis Rd WB to Wallis Rd SB	2 waits for 1
68: Wallis Road SB	10098: Wallis Rd WB to Wallis Rd SB	Passive
10080: Berkshire SB	10098: Wallis Rd WB to Wallis Rd SB	Passive
10096: Wallis Rd WB to Edward	10098: Wallis Rd WB to Wallis Rd SB	Passive
30: Berkshire SB	10099: Wallis Rd WB to Berkshire Rd NB	2 waits for 1
69: Berkshire NB	10099: Wallis Rd WB to Berkshire Rd NB	2 waits for 1
10079: Edward to Berkshire LT	10099: Wallis Rd WB to Berkshire Rd NB	2 waits for 1
10096: Wallis Rd WB to Edward	10099: Wallis Rd WB to Berkshire Rd NB	Passive
10097: Edward Rd EB to Wallis	10099: Wallis Rd WB to Berkshire Rd NB	2 waits for 1
10098: Wallis Rd WB to Wallis Rd SB	10099: Wallis Rd WB to Berkshire Rd NB	Passive
30: Berkshire SB	10100: Berkshire Rd SB to Wallis Rd EB	Passive

LINK1	LINK2	STATUS
79: Wallis Road EB	10100: Berkshire Rd SB to Wallis Rd EB	Passive
10097: Edward Rd EB to Wallis	10100: Berkshire Rd SB to Wallis Rd EB	Passive
30: Berkshire SB	10101: Edward to Wallis RT	Passive
68: Wallis Road SB	10101: Edward to Wallis RT	Passive
69: Berkshire NB	10101: Edward to Wallis RT	2 waits for 1
10079: Edward to Berkshire LT	10101: Edward to Wallis RT	Passive
10080: Berkshire SB	10101: Edward to Wallis RT	Passive
10081: Berkshire NB	10101: Edward to Wallis RT	Passive
10096: Wallis Rd WB to Edward	10101: Edward to Wallis RT	2 waits for 1
10097: Edward Rd EB to Wallis	10101: Edward to Wallis RT	Passive
10098: Wallis Rd WB to Wallis Rd SB	10101: Edward to Wallis RT	1 waits for 2
65: Prince Edward Rd DeadEnd WB	10102: Wallis NB to Edward WB LT	Passive
69: Berkshire NB	10102: Wallis NB to Edward WB LT	Passive
10081: Berkshire NB	10102: Wallis NB to Edward WB LT	Passive
10096: Wallis Rd WB to Edward	10102: Wallis NB to Edward WB LT	1 waits for 2
30: Berkshire SB	10103: Wallis NB to Wallis EB RT	2 waits for 1
69: Berkshire NB	10103: Wallis NB to Wallis EB RT	Passive
10081: Berkshire NB	10103: Wallis NB to Wallis EB RT	Passive
10096: Wallis Rd WB to Edward	10103: Wallis NB to Wallis EB RT	1 waits for 2
10097: Edward Rd EB to Wallis	10103: Wallis NB to Wallis EB RT	Passive
10099: Wallis Rd WB to Berkshire Rd NB	10103: Wallis NB to Wallis EB RT	1 waits for 2
10100: Berkshire Rd SB to Wallis Rd EB	10103: Wallis NB to Wallis EB RT	Passive
10101: Edward to Wallis RT	10103: Wallis NB to Wallis EB RT	1 waits for 2
10102: Wallis NB to Edward WB LT	10103: Wallis NB to Wallis EB RT	Passive
30: Berkshire SB	10104: Berkshire SB to Edward WB RT	Passive
65: Prince Edward Rd DeadEnd WB	10104: Berkshire SB to Edward WB RT	Passive
69: Berkshire NB	10104: Berkshire SB to Edward WB RT	2 waits for 1
10096: Wallis Rd WB to Edward	10104: Berkshire SB to Edward WB RT	1 waits for 2
10097: Edward Rd EB to Wallis	10104: Berkshire SB to Edward WB RT	1 waits for 2
10099: Wallis Rd WB to Berkshire Rd NB	10104: Berkshire SB to Edward WB RT	1 waits for 2
10101: Edward to Wallis RT	10104: Berkshire SB to Edward WB RT	1 waits for 2
10102: Wallis NB to Edward WB LT	10104: Berkshire SB to Edward WB RT	2 waits for 1
10103: Wallis NB to Wallis EB RT	10104: Berkshire SB to Edward WB RT	Passive
25: Eastway NB	10105: Buxhall to Eastway LT	2 waits for 1
25: Eastway NB	10106: Eastway NB to Buxhall LT	Passive
25: Eastway NB	10107: Eastway SB to Buxhall RT	2 waits for 1
81: Buxhall Cres WB	10107: Eastway SB to Buxhall RT	2 waits for 1
10106: Eastway NB to Buxhall LT	10107: Eastway SB to Buxhall RT	2 waits for 1
25: Eastway NB	10108: Buxhall Cres to Eastway RT	2 waits for 1
10105: Buxhall to Eastway LT	10108: Buxhall Cres to Eastway RT	Passive

LINK1	LINK2	STATUS
10107: Eastway SB to Buxhall RT	10108: Buxhall Cres to Eastway RT	2 waits for 1
159: Chapman Roundabout	10195: Chapman Entry 1	2 waits for 1
159: Chapman Roundabout	10196: Chapman Entry 2	2 waits for 1
159: Chapman Roundabout	10197: Chapman Entry 3	2 waits for 1
159: Chapman Roundabout	10199: Chapman Exit 1	Passive
159: Chapman Roundabout	10200: Chapman Exit 3	Passive
159: Chapman Roundabout	10201: Chapman Exit 2	Passive
25: Eastway NB	10240: Eastway NB LT Shalbourne	Passive
25: Eastway NB	10241: Eastway SB RT Shalbourne	2 waits for 1
160: Shalbourne Square WB	10241: Eastway SB RT Shalbourne	Passive
10240: Eastway NB LT Shalbourne	10241: Eastway SB RT Shalbourne	2 waits for 1
25: Eastway NB	10242: Shalbourne RT Eastway	2 waits for 1
10241: Eastway SB RT Shalbourne	10242: Shalbourne RT Eastway	2 waits for 1
25: Eastway NB	10243: Shalbourne LT Eastway	2 waits for 1
161: Shalbourne Square EB	10242: Shalbourne RT Eastway	Passive
10242: Shalbourne RT Eastway	10243: Shalbourne LT Eastway	Passive
21: Osborne Rd NB	10244: Osborne NB LT Mallard	Passive
21: Osborne Rd NB	10245: Osborne SB RT Mallard	2 waits for 1
22: Osborne Rd SB	10245: Osborne SB RT Mallard	Passive
10244: Osborne NB LT Mallard	10245: Osborne SB RT Mallard	2 waits for 1
21: Osborne Rd NB	10246: Mallard LT Osborne	2 waits for 1
21: Osborne Rd NB	10247: Mallard RT Osborne	2 waits for 1
22: Osborne Rd SB	10247: Mallard RT Osborne	2 waits for 1
10245: Osborne SB RT Mallard	10247: Mallard RT Osborne	2 waits for 1
10246: Mallard LT Osborne	10247: Mallard RT Osborne	Passive
69: Berkshire NB	10250: Berkshire NB RT Silk Mills	Passive
10248: Berkshire NB Osborne	10250: Berkshire NB RT Silk Mills	Passive
10249: Osborne SB Berkshire	10250: Berkshire NB RT Silk Mills	2 waits for 1
10249: Osborne SB Berkshire	10251: Osborne SB LT Silk Mills	Passive
10250: Berkshire NB RT Silk Mills	10251: Osborne SB LT Silk Mills	1 waits for 2
30: Berkshire SB	10254: Leabank WB LT Berkshire	2 waits for 1
30: Berkshire SB	10255: Leabank RT Berkshire	2 waits for 1
69: Berkshire NB	10255: Leabank RT Berkshire	2 waits for 1
10254: Leabank WB LT Berkshire	10255: Leabank RT Berkshire	Passive
30: Berkshire SB	10256: Berkshire SB LT Leabank	Passive
30: Berkshire SB	10257: Berkshire NB RT Leabank	2 waits for 1
69: Berkshire NB	10257: Berkshire NB RT Leabank	Passive
10254: Leabank WB LT Berkshire	10257: Berkshire NB RT Leabank	Passive
10255: Leabank RT Berkshire	10257: Berkshire NB RT Leabank	1 waits for 2
10256: Berkshire SB LT Leabank	10257: Berkshire NB RT Leabank	2 waits for 1

LINK1	LINK2	STATUS
10006: Silk RT Osborne	10248: Berkshire NB Osborne	1 waits for 2
10006: Silk RT Osborne	10249: Osborne SB Berkshire	1 waits for 2
10006: Silk RT Osborne	10250: Berkshire NB RT Silk Mills	1 waits for 2
10006: Silk RT Osborne	10007: Silk LT Berkshire	Passive
10007: Silk LT Berkshire	10249: Osborne SB Berkshire	1 waits for 2
79: Wallis Road EB	10103: Wallis NB to Wallis EB RT	Passive
30: Berkshire SB	10350: Rahim LT Berkshire	2 waits for 1
30: Berkshire SB	10351: Rahims RT Berkshire	2 waits for 1
69: Berkshire NB	10351: Rahims RT Berkshire	2 waits for 1
10350: Rahim LT Berkshire	10351: Rahims RT Berkshire	Passive
30: Berkshire SB	10352: Berkshire RT Rahims	2 waits for 1
69: Berkshire NB	10352: Berkshire RT Rahims	Passive
10351: Rahims RT Berkshire	10352: Berkshire RT Rahims	1 waits for 2
30: Berkshire SB	10353: Berkshire LT Rahims	Passive
195: Rahims EB	10353: Berkshire LT Rahims	Passive
10352: Berkshire RT Rahims	10353: Berkshire LT Rahims	1 waits for 2
1: Chapman Road NB	10019: felstead to chapman RT	2 waits for 1
9: Gainsborough Street SB	10061: Gainsborough to Felstead SB RT	Passive
11: Prince Edward SB	10074: Edward SB to felstead WB RT	Passive
5: Eastway SB	10045: osborne to eastway LT	2 waits for 1
5: Eastway SB	10046: osborne to eastway RT	2 waits for 1
5: Eastway SB	10047: eastway to osborne NB RT	2 waits for 1
5: Eastway SB	10048: Eastway to osborne SB LT	Passive
5: Eastway SB	10107: Eastway SB to Buxhall RT	Passive
5: Eastway SB	10108: Buxhall Cres to Eastway RT	2 waits for 1
5: Eastway SB	10241: Eastway SB RT Shalbourne	Passive
5: Eastway SB	10242: Shalbourne RT Eastway	2 waits for 1
1: Chapman Road NB	10000: Chapman NB to Felstead	Passive
52: Chapman Road SB	10000: Chapman NB to Felstead	2 waits for 1
10000: Chapman NB to Felstead	10019: felstead to chapman RT	2 waits for 1
10000: Chapman NB to Felstead	10020: chapman SB to felstead	1 waits for 2
30: Berkshire SB	10001: Primary School EB	Passive
30: Berkshire SB	10002: Primary School WB	2 waits for 1
30: Berkshire SB	10003: Berkshire NB to School	2 waits for 1
69: Berkshire NB	10003: Berkshire NB to School	Passive
10001: Primary School EB	10003: Berkshire NB to School	2 waits for 1
30: Berkshire SB	10004: School WB RT on Berkshire	2 waits for 1
69: Berkshire NB	10004: School WB RT on Berkshire	2 waits for 1
10002: Primary School WB	10004: School WB RT on Berkshire	Passive
10003: Berkshire NB to School	10004: School WB RT on Berkshire	2 waits for 1

LINK1	LINK2	STATUS
10005: Left Turn Wick to Eastway	10011: chapman to eastway NB	Passive
44: Chapman Road NB	10017: Chapman NB to Wick WB	Passive
10011: chapman to eastway NB	10017: Chapman NB to Wick WB	Passive
10014: eastway to wick SB	10017: Chapman NB to Wick WB	Passive
162: Mallard Close SB	10245: Osborne SB RT Mallard	Passive