# Development of mathematical models to improve road freight movements for tunnel infrastructure using Connected and Autonomous Vehicles

by

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## Thesis

submitted to the University of Warwick for the degree of

## Doctor of Philosophy in Engineering

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*Dedicated to my Babaji.*

*Thank you for all your blessings, inspiration and support. I owe this to you!*

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# Declaration

This thesis is submitted to the University of Warwick in support of my application for the degree of Doctor of Philosophy. It has been composed by me and has not been submitted in any previous application for any degree.

The work presented (including data analysis) was carried out by the author. Parts of this thesis have been published by the author and a list of publications has been included in this thesis.

Kushagra Bhargava

# Abstract

Road freight transportation is considered the backbone of country's socio-economic framework and thus its vital to ensure it is working optimally. The research detailed in this thesis is focused on improving the movement of road freight, especially for hazardous goods vehicles via a road tunnel, with the help of Connected and Autonomous Freight Vehicles (CAV-F). The study analyses real-world Dartford Crossing tunnel data to identify the impact of existing check and allow procedures for Dangerous Goods Vehicles (DGVs) and Abnormal Load Vehicles (ALVs) at a tunnel. A near realistic traffic simulation model is developed as part of analysis and is validated against an independent Highways England's Motorway Incident Detection and Automatic Signalling (MIDAS) data. The effectiveness of CAV-F in improving road traffic conditions is measured using different simulation scenarios involving mixed traffic (i.e. CAV-F and conventional vehicles alongside) and different real-world tunnel closure conditions. Once the effective performance of CAV-F is established, this research develops a novel mathematical model aimed at automating the check and allow procedures for DGVs at the tunnel. The mathematical model calculates the geo-reference locations for the placement of cooperative communications between the vehicles and road infrastructure to generate dynamic vehicular gaps. This will allow desired safety gaps between the platoon of DGVs and its preceding and following vehicles enabling isolated travel via the road tunnel to ensure safe and secure passage. The mathematical model is verified for different road layouts determined based on geo-referenced locations, approaching a road tunnel. Using traffic simulation, the results determine if the modulation of vehicles' speeds at identified geo-referenced locations are suitable for desired gap generation. Finally, to conclude the research questions, the second mathematical model is developed to help uninterrupted traffic merging at the junctions, as was observed after the successful gap generation. This model could also be generalised to optimise the traffic merge sequence at a motorway junction. The approach is inspired by the noise cancellation technique which utilises destructive wave interference patterns, where vehicular flow on two merging roads is considered as traffic waves. By analysing the merge sequence of vehicles at the junction from fixed equidistant positions on separate roads, the dynamic phase shifting is applied by modulating the speeds of the identified vehicles which would otherwise approach at the junction simultaneously, leading to queue formation (or collision). The performance of the approach is then measured using a traffic simulation model and are determined against

existing real-world traffic flow on motorways for improvements in travel time, and traffic throughput and reduction in congestion, with increasing traffic density.

# List of Abbreviations

| | |
|---|---|
| **AADT** | Annual Average Daily Traffic |
| **AADTC** | Annual Average Daily Tunnel Closured |
| **AAHT** | Annual Average Hourly Traffic |
| **AAHTC** | Annual Average Hourly Tunnel Closures |
| **ACC** | Adaptative Cruise Control |
| **ACC** | Adaptative Cruise Control |
| **ADAS** | Adaptive Driver Assistance Systems |
| **ADR** | The European Agreement concerning the International Carriage of Dangerous Goods by Road |
| **ALVs** | Abnormal Load Vehicles |
| **AMQL** | Average Maximum Queue Length |
| **AMTICS** | Advanced Mobile Traffic Information and Communication System |
| **AMTT** | Average Maximum Travel Time |
| **API** | Application Programming Interface |
| **ATD** | Average Traffic Density |
| **ATM** | Active Traffic Managements |
| **ATTM** | Average Travel Time Measurements |
| **Autopilot** | AUTOmated driving Progressed by Internet of Things |
| **AV** | Autonomous Vehicles |
| **AVTT** | Average Vehicle Travel Time |
| **BLEVE** | Boiling Liquid Expanding Vapour Explosion |
| **C2C** | Car to Car |
| **C2X** | Car to Everything |
| **CACC** | Cooperative Adaptative Cruise Control |
| **CACS** | Comprehensive Automobile Control System |
| **CAD** | Connected and Automated Driving |
| **CA-DGVs** | Connected and Autonomous Dangerous Goods Vehicles |
| **CAM** | Cooperative Awareness Message |
| **CAM** | Connected and Automated Mobility |
| **CAV** | Connected and Autonomous Vehicles |
| **CAV-F** | Connected and Autonomous Freight Vehicles |
| **CCAV** | Centre for Connected and Autonomous Vehicles |
| **CCTV** | Closed-Circuit Television |
| **C-ITS** | Cooperative and Intelligent Transportation Systems |
| **CIVS** | Cooperative Vehicle-Infrastructure Systems |
| **CNN** | Connected and Cooperative Navigation |
| **COM** | Component Object Model |
| **DENM** | Decentralized Environmental Notification Message |
| **DfT** | Department for Transport |

| | |
|---|---|
| **DG-QRAM** | Dangerous Goods Quantitative Risk Analyses Model |
| **DGVs** | Dangerous Goods Vehicles |
| **DIS** | Driving information subsystem |
| **DRIVE** | Dedicated Road Infrastructure for Vehicle Safety in Europe |
| **DSRC** | Dedicated Short-Range Communication |
| **EBL** | Emergency electronic Braking Light |
| **ETSI** | European Telecommunications Standards Institute |
| **FHB** | Forward Holding Bay |
| **GPS** | Global Positioning System |
| **HGVs** | Heavy Goods Vehicles |
| **HMI** | Human Machine Interface |
| **ITS** | Intelligent Transportation Systems |
| **J1A** | Junction 1A |
| **KMA** | Kent Marshalling Area |
| **LTE** | Long-Term Evolution |
| **MAP** | Map Data |
| **MIDAS** | Motorway Incident Detection and Automatic Signalling |
| **MILP** | Mixed Integer Liner Program |
| **MOBIL** | Minimizing Overall Braking Decelerations Induced by Lane Changes |
| **NROW** | No Right of Way |
| **OVRV** | Optimal Velocity with Relative Velocity Mode |
| **PROMETHUS** | Programme for a European Traffic with Highest Efficiency and Unprecedented Safety |
| **PV** | Platoon-Velocity |
| **PVP** | Public service vehicle priority subsystem |
| **QRA** | Quantitative Risk Analyses |
| **QRAM** | Quantitative Risk Assessment Model |
| **RACS** | Road/Automobile Communication System |
| **RDB** | Route display board subsystem |
| **RGS** | Route Guidance System |
| **ROW** | Right of Way |
| **RSU** | Road-Side Unit |
| **SAE** | Society of Automotive Engineers |
| **SARTRE** | Safe Road Trains for the Environment |
| **SMCALO** | Smart Motorways CALibration and Optimisation |
| **SPaT** | Signal Phase and Timing |
| **SRN** | Strategic Road Networks |
| **TDVPR** | Time-Dependent Vehicle Routing Problem |
| **TEN-T** | Trans-European Transport Network |
| **TIS** | Traffic incident information subsystem |
| **UK** | United Kingdom |
| **UN** | United Nations |
| **UNECE** | United Nations Economic Commission for Europe |
| **URN** | Urban Road Networks |

**V2I** Vehicle-2-Infrastructure
**V2V** Vehicle-2-Vehicle
**V2X** Vehicle-2-Everything
**VAP** Vehicle Actuated Programming
**VisVAP** Visual Vehicle Actuated Program
**VSL** Variable Speed Limit
**VSPD** in-Vehicle SPeeD limits
**WSN** Wireless Sensor Networks
**WSN** Wireless Sensor Networks

# Inclusion of Published Work

As part of the research presented in this thesis, four publications were produced. Two of the publications were in peer reviewed journals. One publication was in peer reviewed conference. A list of the publications is presented below along with a reference to the thesis chapters (and sections). For each of the publications, the author of this thesis was solely responsible for creating the knowledge and results, and the named others provided comments only for modifications of the manuscript.

### Peer Reviewed Journals

- *Bhargava, K., Choy, K.W., Jennings, P.A. and Higgins, M.D., 2021. Novel mathematical model to determine geo-referenced locations for C-ITS communications to generate dynamic vehicular gaps. IET Intelligent Transport Systems.*

The publication details the novel mathematical model aimed at determining geo-reference locations for dynamic cooperative communications to be established, allowing the generation of dynamic vehicular gaps between the Dangerous Goods Vehicles (DGVs) and their neighbouring vehicles, such that they could travel via a tunnel as a platoon and in isolation. This is to ensure the safe movement of DGVs via a tunnel in line with ADR regulations on tunnel safety. The contents of this publication have been discussed in chapter three. The author designed and conducted the study. Other named authors reviewed the design prior to the study being carried out and provided comments to the manuscript. The author approved the final publication.

- *Bhargava, K., Choy, K.W., Jennings P.A. and Higgins, M.D. Novel Road Traffic Merging Strategy using Destructive Traffic-Wave Interference for Autonomous Vehicles. pp. 1-10. (Under review)*

The publication mentions the novel technique utilising destructive wave interference patterns for congestion relief by optimising the traffic merging at a motorway junction. The approach is inspired by the noise cancellation wave patterns. The contents of this publication have been discussed in chapter four. The author designed and conducted the study. Other named authors reviewed the design prior to the study being carried out and provided comments to the manuscript. The author approved the final publication.

- *Bhargava, K., Choy, K. W., Jennings, P. A., Birrell, S. A., & Higgins, M. D. (2020). Traffic Simulation of Connected and Autonomous Freight Vehicles (CAV-F) using a data-driven traffic model of a real-world road tunnel. Transportation Engineering, 2, 100011.*

Publication was aimed to determine the feasibility of increasing the traffic throughput at the tunnel by replacing conventional freight vehicles with CAV-F in a real-world Dartford-Thurrock Crossing Tunnel in Kent, UK. The contents of this publication have been discussed in chapter two. The author designed and conducted the study. Other named authors reviewed the design prior to the study being carried out and provided comments to the manuscript. The author approved the final publication.

### Peer Reviewed Conference

- *K. Bhargava, M. D. Higgins, K. W. Choy and P. A. Jennings, "Traffic Simulation of Connected and Autonomous Freight Vehicles to Increase Traffic Throughput via Road Tunnel Networks," 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium, 2020, pp. 1-5, doi: 10.1109/VTC2020-Spring48590.2020.9128697.*

The published conference paper discusses the usefulness of CAF-F vehicles in improving congestion and travel time only with a small proportion of overall road traffic i.e. DGVs and Abnormal Load Vehicles (ALVs) being simulated as autonomous vehicles alongside conventional vehicles. The study uses PTV Vissim for simulating a real-world tunnel traffic scenario based on the data obtained for Dartford Thurrock River Crossing Tunnel, Kent, UK. The contents of this publication have been discussed in chapter two. The author designed and conducted the study. Other named authors reviewed the design prior to the study being carried out and provided comments to the manuscript. The author approved the final publication.

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# Chapter 1

# Introduction

Road traffic problems such as congestion, travel time, delays, environmental pollution and ever-increasing surges in traffic have always been a socio-economic concern. Urbanisation, economic development, reduced vehicle prices along with increased demand in home deliveries due to online shopping behaviours have largely contributed to the increase of road traffic flow. Due to the rise in population and housing prices in urban areas, people are either willing to relocate to city outskirts or prefer to commute long distances. These decisions adversely impact the traffic on existing road infrastructure and leads to increased congestion and travel time. By estimating the number of passenger car users around the world, their total number has increased by 16% in last three years [1]. Another statistical report from Department for Transport (DfT), the United Kingdom (UK) [2] showed a substantial rise in vehicles on UK roads over the period of last five years. The number of cars & taxis in the UK has risen by 5.9%, vans by 22.4%, Heavy Goods Vehicles (HGVs) by 9.6% and bicycles by 5.2%. This increase has a direct correlation to the drop in UK's public transport, an overall decrease of 11.4% and 28.2%, over the period of last five and ten years, respectively. The number of HGVs has also increased with the development of cities and rise in demand for carrying goods in and around the city. With this inflation of road traffic, the congestion has increased considerably [3]. As per INRIX report [4] it is estimated that on average drivers in the United States spent 56 hours per year struck in traffic. The longest traffic jam recorded was in China, 2010, spanning to approximately 100 kilometres and lasted for weeks [5]. These are some extreme examples of traffic chaos.

The problem of congestion could be related to a classic model of demand and supply [6]. The demand here refers to the reasons for the travel mainly due to work, leisure or emergency activities. The supply refers to the infrastructure supporting the travel such as roads, bridges, tunnels, public transportation, etc. This behaviour of the demand can somewhat be controlled and altered by promoting car share, regulating congestion charges, work parking charges or by providing work from home and cycle to work schemes. But the same cannot be said about the supply of infrastructure to support the travel, which has significant economic cost for expanding and building new roads, bridges, and tunnels. This also temporarily increases congestion and puts strain on alternative routes. The paper [6] classifies the congestion bottlenecks into two categories:

- Recurring – due to infrastructure or topological constrains.
- Non-recurring – due to accidents or incidents, planned or unplanned roadworks, rise in demand of travellers or weather conditions.

The human driving behaviour is another major cause for non-recurring congestion. The study [7] highlights the congestion contribution by the varied behaviour of human drivers toward unexpected incidents or road closures. The study states that this is one of the most significant contributors of congestion, between 50%-55% [8]. Even though tough traffic laws and regulations are in place with heavy penalties and strict prosecutions, the human driving errors and competitive driving still contributes largely to roadside incidents and accidents. In economic terms, the road transportation problems have significant decremental impact on a country's economy, especially on developing nations [3] and could cost up to 5% of the country's GDP [1].

## 1.1. Road Freight Transportation and Road Tunnels

The road freight transportation is considered one of the major indicators of the country's growth and economic development. The movement of freight in directly proportional to the variations of global economic markets. This correlation can be clearly observed with the increase in freight prior to global recession of 2008, a decline during the recession and followed by a gradual increase following the recovery from it [9], as shown in Figure 1 to support the variances in freight movement.

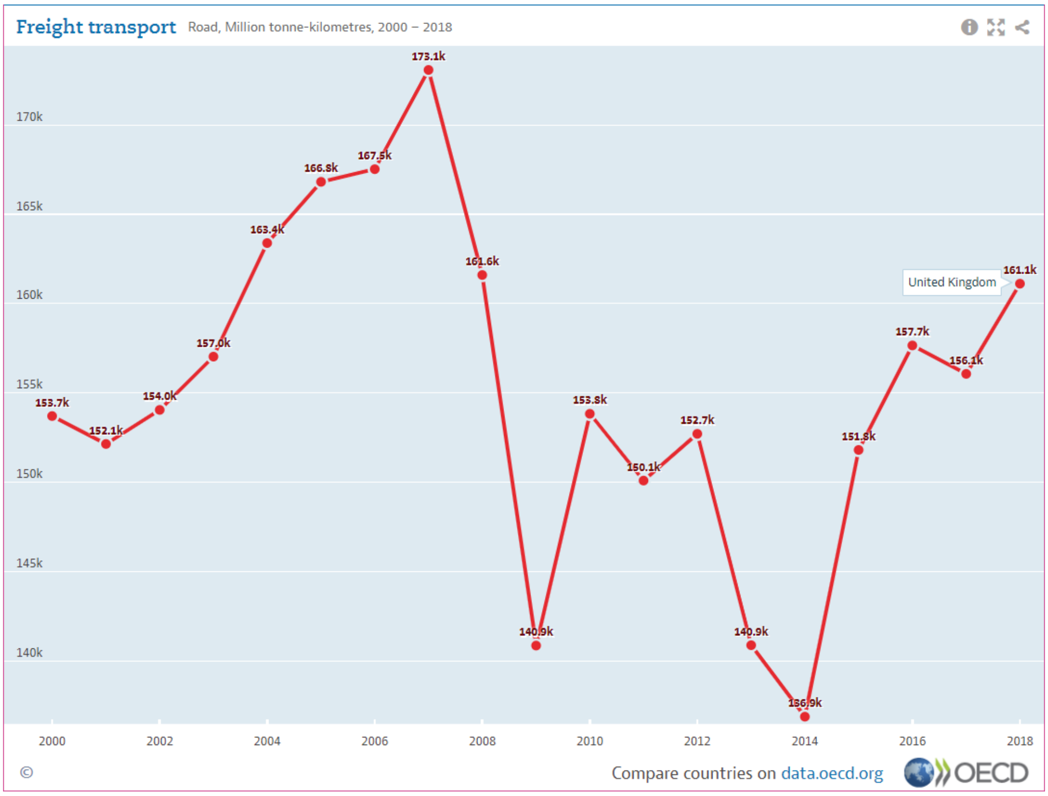


*Figure 1 Freight transportation Road, Million tonne-kilometres, 2000-2018, UK*

Due to these measures the number of HGVs and DGVs have continued to rise [10]. Because of high socio-economic influence of the freight transportation, it is no surprise that freight transport is also one of the major contributors of traffic related problems such as congestion, environmental pollution, and road accidents [11]. To improve the handling and transportation of freight goods, various methods such as traffic management, routing systems, intelligent transportation system, etc. have been used successfully in past. As an example, at cargo ports, the intelligent freight transportation methods have proven to be very effective in increasing the ports efficiency by reducing the cost and time delays [12]. Although these systems are static in nature and work as pre-programmed instructions in a controlled environment, the benefits of having an automated system cannot be ignored. By automating and eliminating the human driver, the goods & delivery vehicles will continue to work for longer hours in an efficient way. Other paper [13, 14] studied the congestion scenario for freight transportation which followed a set period of time to deliver goods. It proposed the Time-Dependent Vehicle Routing Problem (TDVPR) solution to ease the freight congestion based on historical data obtained from archived traffic data, real-world road network data and Google Map API to produce distance and travel time matrix. Utilising intelligent transportation methods, a Connected and Autonomous Vehicles (CAV) enabled freight transportation system will be able to provide solutions to drayage routing, delivery routing/scheduling and international border policy problems by effectively coordinating with intra-country road infrastructure, depots and ports [12]. A previous study [15], mentioned the use of autonomous vehicles to improve the supply chain for freight transportation using computer aided technologies. It studied the operational model of autonomous road freight transportation within metropolitan areas. The research conducted by [15] was aimed at understanding the risks and benefits by modelling overall freight transportation system in urban areas. A Zenzic Roadmap 2030 report [16] highlighted the benefits of the early adoption of Connected and Automated Mobility (CAM) ecosystem by freight and logistics. In the post-COVID-19 era, automated freight & logistics would help enable robust supply chains with self-driving vehicles for last mile journeys, especially in cases of lockdown and to vulnerable age groups with human-free deliveries. Also, given the flow pattern of freight involves less human involvement, the CAM implementation could be prioritised. The report not just focused on improving the freight movement, but also highlighted key milestones till 2030 for successful transition from current conventional road transport model to CAM model. Some of the key milestones mentioned include creation of test beds for CAM testing, establishing of standards, legislation and policies and data communication and sharing formats, development of artificial intelligence and machines learning models for safer and resilient automated vehicles and infrastructure, etc.

Focusing on hazardous freight carrying vehicles referred as Dangerous Goods Vehicles (DGVs), as shown in Figure 2, require additional regulations and risk assessment checks before they could make a journey through a transportation network [17].

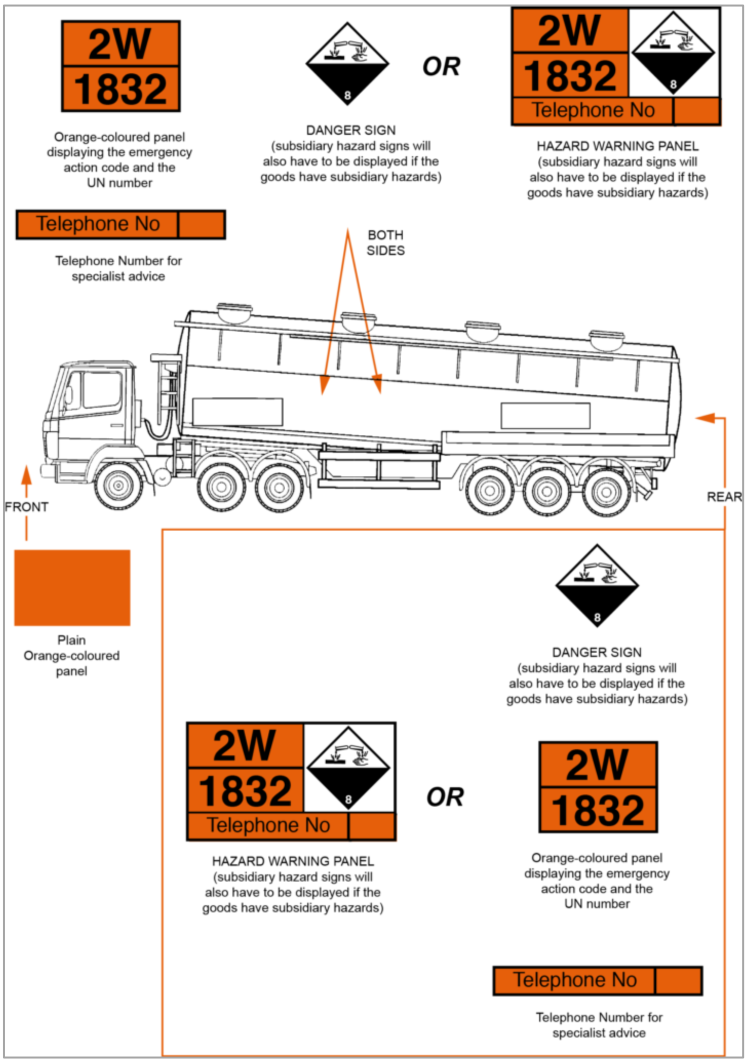


*Figure 2 Illustration of DGVs and mandatory ADR labels and markings on the vehicles [18].*

The reason for this complex and lengthy processes is the type of hazardous goods they carry, which if not dealt with care could lead to fatal and environment damaging scenarios such as fires, explosions, and release of toxic and radioactive materials. As a reminder, the tragedies of 1999, a couple of months apart in Mont Blanc [19] and Tauern [20] road tunnels highlights the paramount importance of tunnel safety. Many such incidents have and could lead to high fatality rates, damages to tunnel infrastructure and environment, and significant socio-economic impacts due to long closures and diverted routes. [21]. A quantitative risk analysis was performed [22] focused on DGVs in the Trans-European, Singapore and Chinese tunnels and understanding *'when, how and what'* scenarios of accidents and risks involving DGVs. A comparison with open roads was also made to see how risks may change and concluded that either of the road conditions are risky for other road users [22] [23]. Although the accident rates are lower in tunnels, but when they happen the number of serious incidents and fatalities are significantly higher than that on open roads [24]. It was shown that the reason for tunnels to be safer is related to the cautious behaviour of the human drivers and slower driving speeds, although driving in tunnels could have a psychological impact of driving in a closed and homogeneous environment which could increase the chances of accidents [25]. The paper also highlighted that shorter tunnels are more prone to accidents than longer tunnels and most accidents happen at the entrance of a tunnel. Which seems contradictory to the European Directive 2004/54/EC [17] which applies to tunnels longer than 500 meters. Another study [26], identified that the bi-directional tunnels are more dangerous than the unidirectional tunnels and factors such restricting the flow of DGVs and HGVs, minimum 150 meters distance between freight vehicles, improved ventilation and exit points are critical for ensuring the tunnel safety. Following the Mont Black and Tauern tunnel incidents, UNECE published a report [21] with recommendations to ensure the safety of tunnel systems on factors namely road users, operation in tunnels, infrastructure and vehicles. The driver must be educated and trained on tunnel procedures. The drivers of DGVs must undergo special training procedures to handle the goods and safety of other road users, especially in a tunnel. The tunnels must be equipped with ventilators, sensors, CCTVs, thermal cameras, smoke and toxic gas detectors, temperature control systems, exit routes, continuous monitoring and management of traffic flow, etc., and should be kept up to date with technological advances. A Quantitative Risk Analyses (QRA) is recommended to ensure the tunnels in EU are compliant with Directive 2004/54/EC [17] and is safe for normal and DGVs. Many QRA methods are used, such as OECD/PIARC QRA Mode [27] and DG-QRAM [22], etc. The UN's ADR document [28], first issued in 1957, details the procedures and restrictions on hazardous goods, their consignment procedures, use of means of transportation and implied restrictions on their international movement.

Some crucial points were noted in this report [29] regarding the planning of freight travel via the tunnel by the lorry drivers or the agencies to ensure their supply chain is not affected and deliveries are made on time. The tunnel routes are considered crucial and preferred to others in order to save time and ensure quick deliveries. Thus, to pre-plan their journey, they depend on tunnel's website to identify tunnel restrictions and dimensions or on satellite navigational information, which are sometime not allowed by their employers due to lack of updates or inaccuracies. The information is accurately determined when approaching the tunnel which could then lead to delays and in extreme cases fines for not adhering to specific tunnel rules, like at Dartford Thurrock River Crossing Tunnel in Kent, UK. [30]. The availability of information on the tunnel's restrictions and dimensional is a crucial aspect and providing this information by the means of Cooperative and Intelligent Transportation Systems (C-ITS) communication to approaching freight vehicles at appropriate distance, like at a cargo port or the last crucial turn to a tunnel, would help drivers plan ahead of necessary changes to their driving patterns including route planning, change of driving shifts, etc.

## 1.2. A CAV Solution?

So, to improve the traffic related problems, are the CAVs the solution? When mentioning CAV related technologies, the distinction must be made between AVs and CAVs. A report by DfT [31] defines autonomous vehicles (AVs) as a vehicle that "*is designed to be capable of safely completing journeys without the need for a driver in all normally encountered traffic, road and weather conditions*". On the other hand, the connected vehicles, fitted with communications devices or built-in machine telematics, provides information to either the driver or to the vehicle, allowing them to collaborate with other road users and road infrastructure. With artificially intelligent automotive technology becoming mainstream, the humans will start taking a passenger seat and would play a new role of supervising the workings of an intelligent vehicle. The primary goal of CAV is to improve the road safety by minimising the road fatalities which are caused by human errors. By replacing or assisting the human driver, CAV promises a substantial reduction in number of road fatalities [32]. This significant benefit could be fully achieved given a Society of Automotive Engineers (SAE) Level 4 (highly automated) or Level 5 (full automated) vehicle starts dominating the roads around the world.

The inclusion of intelligent vehicle technologies to make the transportation safer, efficient and environmentally cleaner is not a recent development but dates back to 1970s [3]. In Japan, the Comprehensive Automobile Control System (CACS) project [33], was initiated which focused on easing congestion, pollution, accidents and increased acceptance of automobiles by using computer aided systems. The project worked on developing five subsystems, namely,

- Route Guidance System (RGS)
- Route display board subsystem (RDB)
- Driving information subsystem (DIS)
- Traffic incident information subsystem (TIS)
- Public service vehicle priority subsystem (PVP)

The seven year CACS project paved the way for future development such as RACS (Road/Automobile Communication System) [34] and AMTICS (Advanced Mobile Traffic

Information and Communication System) [35]. These projects were first examples of navigational system and traffic management system which are now used extensively to monitor and control the road traffic. In Europe, a comprehensive program under the name PROMETHUS, (Programme for a European Traffic with Highest Efficiency and Unprecedented Safety) [36] alongside the DRIVE (Dedicated Road Infrastructure for Vehicle Safety in Europe) project [37], was launched in 1986, which mentioned the use of Vechile-2-Vehicle (V2V) and Vehicle-2-Infrastructure (V2I) solutions for traffic problems. The anti-lock braking system, damaged vehicle warning signals, use of artificial intelligence in V2V and V2I communication architectures, were few areas of development mentioned in the paper.

The idea of autonomous vehicles is also not new and dates back to early 20th century. The press article mentioning "*Phantom Car*" and remote-controlled trials in America in early 1920s and 1930s [38], must have captivated the imaginations of masses and innovators. In 1958, General Motors, tested the first technically driverless car on a one-mile long test track in Michigan [39]. In 1980s and 1990, the development of autonomous vehicles gained momentum and companies such as Mercedes Benz, General Motors, Ford, and Volvo started developing and testing AVs on streets and test areas free of public transport. The projects like PROMETHUS, CACS and DRIVE further supported the developed of technology to help aid driving by machines.

The event in 2005, "*The 2005 DARPA Grand Challenge*" [40], skyrocketed the interest and development activities in the field of autonomous vehicles. Following the challenge, the Google launched their self-driving car program Waymo in 2009 [41] which by now have covered more than 4 million of miles of city road in the US, refining and redefining the self-driving experience for vehicles and riders. In 2011, the Nevada legislation passed the law allowing the autonomous cars to drive on highway [42]. In 2015, the U.S. states of Nevada, Florida, California, Virginia, Michigan and Washington DC allowed the testing of autonomous cars on public roads [43].

The European Commission launched several initiatives and developed a European strategy relating to Connected and Automated Driving (CAD) [44]. Due to CAD initiative various test project are actively in motion, building and testing infrastructure to understanding security and human interaction aspects of CAVs. Below are few examples of current CAD projects in Europe, Digitales Testfeld Autobahn [45], Smart Mobility Schiphol [46], C-Roads [47], L3Pilot [48], Bridging Gaps for the Adoption of Automated Vehicles (BRAVE) [49], INFRAMIX [50], TANGO [51], C2ART [52], etc. In Asia, the market and adoption of CAVs is still in early stages.

Projects like Advanced Safety Vehicle Phase 2 (ASV-2) [53] in Japan, AUTOmated driving Progressed by Internet Of Things (Autopilot) [54] a joint venture with of EU with South Korea, a 100-square-kilometer closed course for testing of autonomous vehicles called National Intelligent Connected Vehicle Pilot Zone [55] in China and Self-driving taxi trials in Singapore with a US-bases start-up company called nuTonomy [56] are some of the important examples showing the development of autonomous vehicles in the east. Figure 3 gives the visual comparison of CAV technologies around the world.

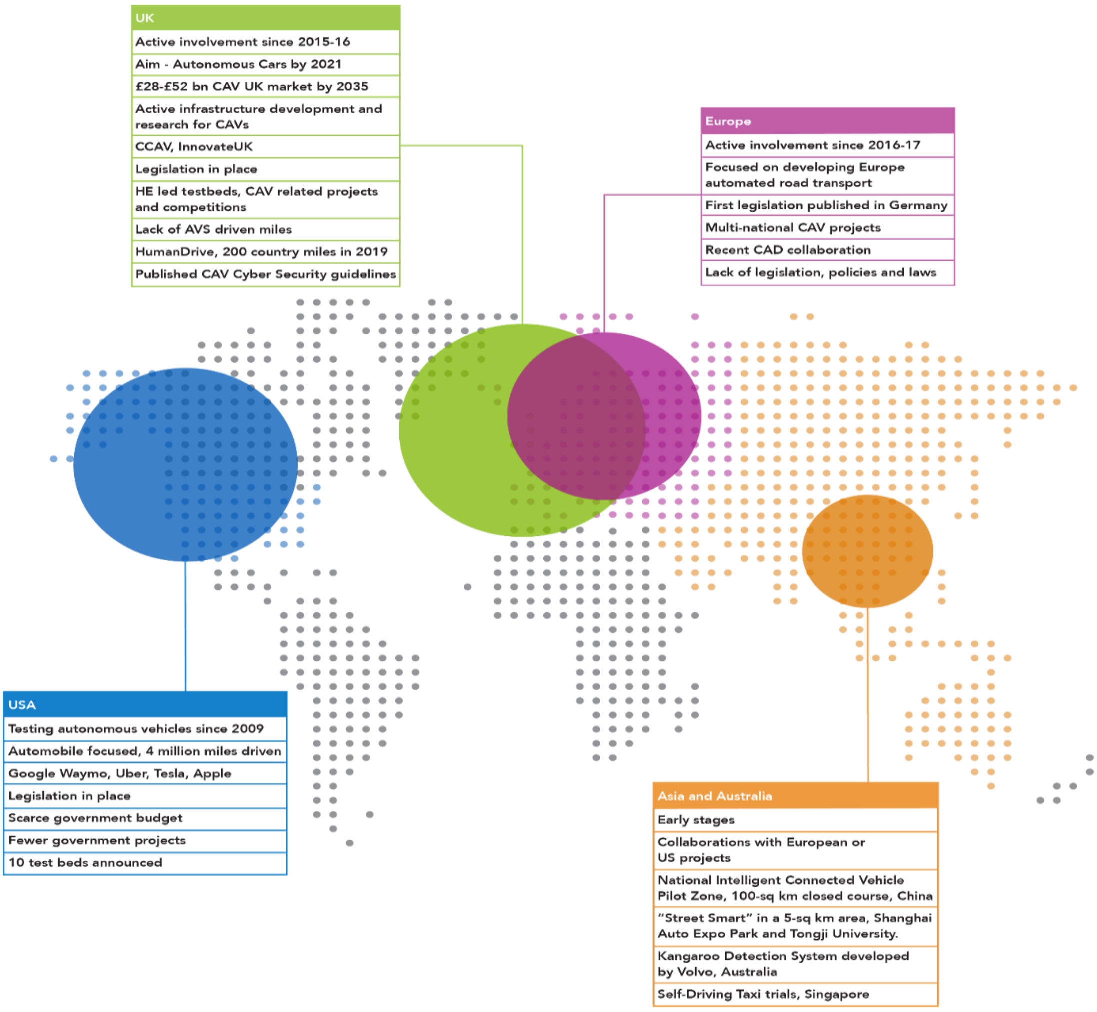


*Figure 3 Comparison of CAV technologies around the world*

Similar initiatives are taken by UK government to accelerate the development and integration of CAV technologies. The Centre for Connected and Autonomous Vehicles (CCAV) [57] was established in 2016 as a joint policy unit of the DfT and the Department for Business, Energy and Industrial Strategy to focus on the development of CAV technologies and infrastructure in UK. In 2016, the UK announced the launch of MERIDIAN [58] project which will create the world's most effective CAV testing cluster in the UK's automotive and technology heartlands between Coventry and London. Recent examples in UK of wrong way driving due to negligence/tiredness of drivers, emphasis more on advocating the case of autonomous vehicles. The CAV rapid development is also putting pressure on development of new regulations and policies to be ready when they arrive. In UK, the review on regulations for driverless cars was published on 11th February 2015 [59] and guidance on 6$^{th}$ August 2017 [60] which covered the best and safest ways to trial automated vehicles on UK roads and take into consideration the potential cyber-attack loop holes. In May 2017, Germany became the first country to have passed legislation on automated driving [61] and presented a ministerial report of an ethics commission on guidelines on automated driving [62]. These guidelines are aimed to help manufactures, developers, construction workers, consumers, etc. when dealing with automated vehicles.

The CAV technologies are determined to provide the solutions to mentioned traffic related problems. With artificial intelligent and automotive technology coming of age, humans will start to take passenger seat and would play a new role of supervising the workings of intelligent vehicles. The primary goals of CAV would be to improve the road safety by minimising the road fatalities caused by human driving errors, reduce congestion and emissions, and minimise travel time. In this research the aim will be to understand and identify the benefits of connected vehicles on road network. Many previous studies have been conducted. In a commercial summary report by Atkins Ltd [63] for DfT, the use case for CAV vehicles was studies for different scenarios such as car-following, lane changing and gap acceleration, from a small mix of CAV and non-CAV vehicles to fully CAV enabled traffic. The study focused on UK's Strategic Road Networks (SRNs) and Urban Road Networks (URN) taking into consideration junctions (both free-flow & controlled), A-roads, urban A-roads, urban traffic signal junctions, pedestrian crossing and dedicated Vehicle-2-Everything (V2X) infrastructures. It showed that CAV is best suited to reduce journey times for congested traffic on SRN with the high fleet of CAV traffic (>75% approximately). This could be because on SRN high speed factor could make CAVs more cautious and might not be able to work with full potential. For other scenarios either the journey time marginally increases or does not change significantly to use CAV over user experience. On the other hand, for URN model even a small fleet of CAVs (25% approximately), showed significant improvements. By this it could be referred that for scenarios where the traffic density is higher, introducing CAVs would surely improve the traffic movements.

The paper [64] assess the benefits of CAV in a simulated environment using MovSim and by analysing simple control strategies such as Adaptative Cruise Control (ACC) with symmetric traffic flow on suburban highways. Though the paper uses restrictive one fixed message from a Road-Side Unit (RSU) to all vehicles in a ramping or lane closure scenarios, it does show improvements on road congestion. Another paper [65] studied the effects of cooperative highway traffic using multi-agent model on a freeway. It aimed to study the physical, communication and trust layers of Vehicle-2-Vehicle (V2V) protocols. The physical and communication factors were considered using the information exchanges from Dedicated Short-Range Communication (DSRC), Wireless communication protocols and other on-board vehicle sensors such as LIDAR or lasers. The trust factor was computed dynamically for direct trust between two vehicles and indirect trust amongst the other vehicles in the group. The study used calibrated Optimal Velocity with Relative Velocity mode (OVRV) [66, 67] and Minimizing Overall Braking Decelerations Induced by Lane Changes (MOBIL) [68] model to mimic realistic traffic conditions. It concluded the importance of trust in information exchanges and highlighted the complex nature of V2V communications.

The platooning behaviour of autonomous vehicles was studied [69] with constant spacing instead of constant time headway, to improve traffic conditions and congestion in urban areas [70]. The simulated study showed promising results in fixed and static platooning scenarios where the lead vehicle is controlling the train. It announces a new plan which gets propagated through all subsequent vehicles. Vehicles hold this information and react to it simultaneously, only when all the vehicles have received the information. This raises a question on how the system will behave if the information is not completely transmitted to all vehicles in given time? Or how to ensure the trust in leader's information? Study does not consider dynamic platooning whereby leader and following vehicles could join and exit the platoons on-demand. The effects of platooning with HGVs are being studied in real-world by the trials conducted in Europe [71] [72], US [73] and UK [74]. The aim of these studies is to understand the potential benefits and risks associated to platoon trains of HGVs on other road users. There are still questions on how to deal with them in on-slip and off-slip scenarios for other vehicles; should platoons be considered an Abnormal Load Vehicle (ALVs); how it gets regulated for tunnels and bridges; what the safety implications are, etc.

Further research, [66], looked at a distributed approach where vehicles communicates with each other for a given radio interaction range for investigate congestion mitigation aspects. It studied the C2X (Car-to-Everything) interactions between infrastructure and driver using Adaptive Driver Assistance Systems (ADAS) [75]. The paper mentioned IEEE 802.11p variants, UMTS, DSRC technologies used in cars and their interactions with Wireless Sensor Networks (WSN), VANETS, OBU and RSU of infrastructure [76]. This way both centralised and de-centralised approaches were taken into consideration, analysing the cooperation between microscopic (short ranges Car-2-Car (C2C) communications) to macroscopic C2X communications for efficient traffic management.

The decision making of autonomous vehicles were reviewed [77] by studying the fleets of AVs and their surroundings. It identified that existing traffic signals rules are insufficient and proposed new rules to handle different type of intersections and lane mergers, based on the results obtained from virtual real-world model. It studied different types of roads and determined certain roads designs such as roundabouts are better carted for AVs, due to significantly fewer conflicting regions in comparison to road crossings. Another separate study [78] focused on discussing the effects of IEEE 802.11p communication protocols for I2V infrastructure in tunnel subsystems in Austria, S1 highway within the ROADSAFE project. It studied the impact and suitability of the communication protocols in tunnels and presents the results on how suitable the communication will be given in low, medium and high-density traffic. It studies the effects of signal strengths from RSUs and OBUs. A separate paper [78] pointed out mounting position of RSU antenna has strong influence when mounted on the height higher than largest vehicle. This seems to suggest that for a better communication from RSU a clear field of area is required. Same applies to OBU mounted on rooftop position to yield the best performance in terms of lowest error ratios. Many such studies have been conducted in the field of CAV relating to the flow of passenger cars, public transport, HGVs in an urban or motorway scenarios, ownership, parking, cyber security, etc. To the best of my knowledge, the effects of CAV enabled DGVs transportation through restricted road structures such as tunnels, bridges and urban areas have not been studied.

In the thesis two type of connected vehicles are referred:

- Connected and Autonomous Vehicles (CAV)
- Connected and Autonomous Freight Vehicles (CAV-F)

The distinction between the two is that in the study CAV category refers to the simulation of autonomous Cars and LGV vehicle types, whereas CAV-F refers to autonomous HGVs/DGVs/ALVs vehicle types as defined and simulated in traffic simulation software PTV Vissim [79] based on CoEXist project [80].

# Chapter 2

# Research Approach

In Chapter 1, it was identified that the use of CAV is surely a solution for most of the traffic related issues. Based on this realisation, this thesis also contributes to the knowledge, by focusing specifically on the benefits of CAV technology on freight movements via a road tunnel infrastructure. Before we discuss the thesis's research approach, it's imperative to understand the existing terminologies like self-driving vehicles, autonomous vehicles and automated vehicles. Clarity of these terms will help baseline the type of technology inferred in this research and will help determine microsimulation models used to analyse the effects of them in improving the movements of freight vehicles via a road tunnel.

As per the SAE J3016 Levels of Driving Automation [81], the driving automation is defined in six levels, Level 0 to Level 5, *'On-road'* definitions, as presented in Table 1.

Table 1 SAE J3016 Levels of Driving Automation

| **Levels** | **Definitions** |
|---|---|
| 0 – No Driving Automation | Full human control. |
| 1 – Driver Assistance | Vehicle can perform either longitudinal or lateral motion control without human intervention, but not capable of complete event detection and response. Human driver in control. |
| 2 – Partial Driving Automation | Vehicle can perform both longitudinal and lateral motion control without human intervention, but not capable of complete event detection and response. Human driver in control. |
| 3 – Conditional Driving Automation | Vehicle capable of dynamic driving tasks but under limited road condition and falls back to human driver of conditions are not met. Human driver in control but only when requested. |
| 4 – High Driving Automation | Vehicle capable of complete dynamic driving tasks under most of the road conditions. Human driver control not required. |

| | |
|---|---|
| 5 – Full Driving Automation | Vehicle in full control under any road conditions.<br>No provision for human driver to control vehicle. |

As per SAE [81], there is further distinction between the definitions of *autonomous*, *automated* and *self-driving*. As per SAE, the *fully autonomous vehicles* is considered to be self-aware and capable of making its own driving choices. In contrast, the *fully automated vehicle* is not self-aware and would follow orders to drive itself. The *self-driving* definition is closer to *automated* than *autonomous* but differ by the fact that the *self-driving vehicles* would be able to operate only in limited conditions with human driver ready to take control when requested. This makes *self-driving vehicles* as Level 3 or Level 4 category and Level 5 is more aligned to fully autonomous.

In my opinion, the definition of *fully autonomous vehicle* is not realistic in the real-world *On-road* scenario as to drive within highways code, the vehicle would require interact with infrastructure for safe and secure driving on urban, rural and motorway roads.

In my thesis, I have used the terms Connected and Autonomous Vehicles (CAV) and Connected and Autonomous Freight Vehicles (CAV-F) in chapter 3 and 4, and Autonomous Vehicles (AV) in chapter 5. The first term, CAV, is defined as a non-freight vehicle equipped with connected vehicle technology to enable V2V and V2I communications and would be able to drive autonomously without human intervention in scenarios such as platooning. The latter term, CAV-F, is same as CAV but only pertaining to freight vehicles. Both these vehicle classifications would be at Level 3 or Level 4. The Autonomous Vehicle (AV) is defined a vehicle which is fully autonomous in terms of driving capabilities but would be capable to interact with infrastructure and neighbouring vehicles to obey priority messages.

## 2.1. Aims & Contributions

The overarching aim of the thesis focuses on improving the road traffic conditions, especially congestion, travel time and traffic throughput, near a road tunnel by the use of connected and autonomous vehicles (CAV, CAV-F and AV). Having briefly discussed the impact of road freight on tunnels and existing CAV solutions, there is a clear socio-economic motivation for this research which aims to improve, optimise and automate DGVs and ALVs movement control procedures using connected freight vehicles to help improve travel time and traffic throughput and reduce congestion.

The first and foremost objective of the research is to analyse the traffic flows and patterns of the real-world Dartford Thurrock Crossing Tunnel, UK. This tunnel was chosen as it is the only known semi-automated tunnel in UK which is equipped with sensors to identify compliant and non-compliant vehicles, allowed to enter the tunnel. Based on the analysed tunnel traffic flow and tunnel closure procedures, two separate traffic simulation scenarios are developed to help determine the impact of them on traffic conditions:

1. With existing scenario involving traffic composition consisting of only conventional vehicles, how will reducing the closure counts or closure durations help improve traffic related problems.
2. By introducing CAV and CAV-F vehicles alongside conventional traffic, how will tunnel closures be impacted and what will be the impact on traffic related problems.

Based on the learning from previous simulations and realising the benefits of CAV-F vehicles in improving traffic concerns at the tunnel, a novel *Dynamic Gap Generation* mathematical model was developed as objective. The aim of the model is to group the CAV-F vehicles travelling towards the tunnel in tandem from various road sections, to passage as platoon via the tunnel, without a need of tunnel closures. The model ensures desire safety gap between the CAV-F platoon and its preceding and following vehicles is established, by determining the optimal geo-referenced locations for relaying speed change information to vehicles, to achieve desired gaps. The communication mechanism to relay speed information is beyond the scope of this thesis.

Following the development of *Dynamic Gap Generation*, it was observed, although the traffic impact of the model was comparatively lower than existing traffic closure scenarios, the slowing traffic was affecting the merge sequences in road scenarios with junctions. To address the issue, a second novel *Destructive Wave Interference* mathematical model was developed, as the last objective of the research. The aim was to allow uninterrupted merging of traffic at the junction by phase shifting the colliding vehicles. This would help reduce the congestion build-up due to slowing *following* vehicles, approaching the junction. The model is inspired by noise cancelling mechanism and the model was proven to be effective with highly autonomous vehicles (Level 4 or Level 5) with no human driving involvement. This second model would also be generalised for any motorway junction and is not restricted to tunnels.

**Error! Reference source not found.** shows how this research is linked with a stepwise and s ystematic progression of identification of research questions, and development and generalisation of research solutions.

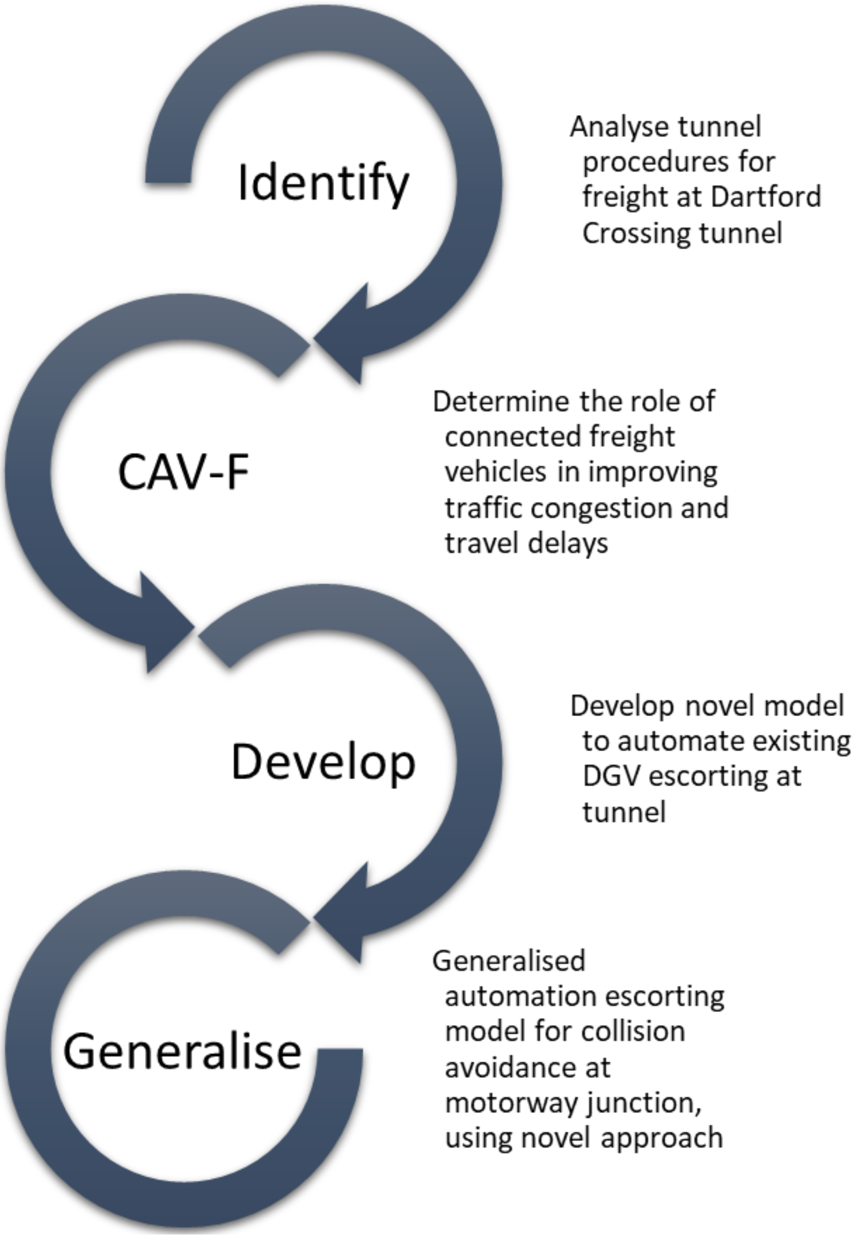


*Figure 4 The stepwise progress of research.*

The subsequent thesis chapters detail the in-depth literature review, methodology, simulation scenarios and results for each of the chapters.

**Chapter 3** studies the real-world Dartford Crossing tunnel to analyse driving patterns and safety procedures to control the movement of DGVs. Three objectives were identified:

- To identify optimal control scenarios where traffic flow at the tunnel could be optimised with conventional vehicles.

- To analyse small proportion of CAV-F vehicles and different autonomous driving behaviours (*Cautions*, *Normal* and *Aggressive*) alongside conventional vehicles in improving traffic congestion and travel time.
- To determine, if by replacing all the freight vehicles by CAV-F, can the higher throughput be achieved on existing infrastructure?

The two published papers in Transportation Engineering journal [82] and IEEE VTC conference [83] are based on this chapter.

**Chapter 4** is a natural progression from Chapter 2. Once the effectiveness of CAV-F vehicles is established, the next question tackled was, how could the escorting and extraction procedures for DGVs be automated using CAV-F and intelligent infrastructure? This chapter discusses the novel mathematical model to determine strategic C-ITS geo-reference location points near a road tunnel to enable dynamic vehicular gap generation. The objective was to mathematically identify appropriate geo-reference location points at which the speeds of *preceding*, *DGVs convoy* and *following* vehicles would be modulated to generate the desired gap i.e. the length of tunnel and should apply to different road layout leading to a tunnel. The published paper, *Bhargava, K., Choy, K.W., Jennings, P.A. and Higgins, M.D., 2021. Novel mathematical model to determine geo-referenced locations for C-ITS communications to generate dynamic vehicular gaps. IET Intelligent Transport Systems*, details the novel mathematical model to enable the dynamic gap generation by appropriately modulating the speeds.

**Chapter 5** builds upon Chapter 3 mathematical model which is defined for a DGVs movement via a road tunnel scenario. This chapter answers the question on how the mathematical model to generate dynamic gaps would be modified to control the traffic movement to allow uninterrupted traffic merging at the junction prior to tunnel after successful gap generation or on a generic motorway approaching a junction. A novel destructive traffic wave interference model is developed, *Bhargava, K., Choy, K.W., Jennings P.A. and Higgins, M.D. Novel Road Traffic Merging Strategy using Destructive Traffic-Wave Interference for Autonomous Vehicles. (Under review) pp. 1-10*, which aimed at reducing the congestion at the merger by enabling slot-based traffic movement i.e. gaps are generated on motorway and on approaching junction resembling a square wave pattern where crest resembles vehicle group and trough an empty gap. At the junction two traffic wave patterns merge inversely.

**Chapter 6** presents the over discussion on the contributions of this research. While each chapter has its own discussion and summary of the results, an overarching discussion has been presented to link each aspect of this research and findings with the overall aim of the research. This chapter also discusses the merits and limitations of this research and possible future work that might follow the work already presented in this thesis.

**Chapter 7** provides the final conclusions from the research work presented in this thesis.

## 2.2. Traffic Simulation Modelling

The results in individual chapters are analysed using a traffic simulation software, PTV Vissim version 11 and 2020 (SP12), and to prove the mathematical formations relating to dynamic gap generation model and destructive traffic wave interference model. Other traffic simulation models such as C++ based SUMO (Simulation of Urban Mobility) [84] and Java based MovSim (Multi-Model Open-Source Vehicular-Traffic Simulator) [85, 86] were also considered.

SUMO is an open-source [87] licenced simulation software which is suitable for modelling of intermodal traffic systems including road vehicles, public transport, and pedestrians. It support tools to handle route finding, visualization, network import and emission calculation. SUMO can be enhanced with custom models and provides various APIs to remotely control the simulation. Implemented in C++ and only utilising portable libraries, it features explicit modelling or multi-modal traffic simulations and control of vehicles, pedestrians and public transport using TraCI. Ability to support unlimited number of simulated vehicles with no limitation on network size and ability to simulate timer scheduled traffic lights control. It also supports import formats such as OpenStreetMap, PTV Visum, PTV Vissim and NavTeq.

MovSim is an open-sourced Java software and is a lane-based traffic simulator which is capable of implementing various car-following models such as simplified Gipps, Intelligent Driving Model (IDM), Enhanced IDM/Adaptive Cruise Control Model, Krauss Model, etc. detailed in [88-90]. It is based on MOBIL strategy [91] for lane change related to acceleration (but could be extended to other models). Available as command line or as graphical user interface. MovSim also provides a physics-based fuel-consumption model to calculate consumption on an individual or collective level.

The PTV Vissim simulation is chosen because of an ability to simulating car-following behaviour with stochastic element between different simulations to mimic real world scenarios. The model used is based on Wiedemann 74 [92] and Wiedemann 99 [93] car-following model which takes into account the traffic flow patterns and analysis of congestion waves caused by lane changing, merging, and check and allow procedures. The Wiedemann 74 driving behaviour is used to simulate urban roads surrounding the tunnel and Wiedemann 99 model with a slow-lane rule is used to simulate main A-road leading to the Dartford Crossing tunnel. The model is capable of simulating the irregular human driving behaviour along with physical properties of a vehicles based on braking, acceleration, desired speed and minimum braking and driving distance at different speed profiles. The simulations are deterministic and are calibrated prior to each new set of simulations to ensure the traffic behaviour is modelled correctly, based on the statistical analysis of the tunnel data obtained from Highways England.

The PTV Vissim is also capable of simulating the driving behaviour of CAV enabled vehicles based on the European project '*CoEXist*' [80] and has defined pre-defined driving behaviour parameters; acceleration and deceleration functions; and speed and time distributions for autonomous vehicles [79]. For the experiments, the CAV-F vehicles are defined between three driving logics, as identified by CoEXist project:

- *AV-Cautious*: vehicle observes all road-codes and drives more cautiously than human driver leaving wider gaps between vehicles.
- *AV-Normal*: human-like driving with additional capabilities of utilising on-board vehicle telemetric information.
- *AV-Aggressive*: perfect CAV or AV driving to enhance cooperative driving with small headway in possibly all road conditions.

PTV Vissim is capable of simulating traffic sequences and emission modelling along with the COM (Component Object Model) interface to control the behaviour of traffic simulation using external programming scripts such as Python. PTV Vissim is also used in commercial projects for traffic modelling and this advantage is also considered when deciding the use of Vissim simulation software for this research.

Using the Vissim, the study will only be able to study the changes in driving behaviour of the vehicles and their improvements on the traffic conditions in normal driving scenarios. It will not be able to carter external factors such as incidents, accidents, or vehicle failures due to the deterministic nature of Wiedemann models.

# Chapter 3

# CAV-F Impact on Road Tunnel Traffic

One of the fundamental questions is, what are the impacts of the approaching DGVs and ALVs on the road traffic leading to a road tunnel. Road tunnels are a more complex road infrastructure than open roads due to the higher safety and security concerns for all road users and the physical structure of the tunnels [25]. Additional restrictions observing the European Agreements concerning the International Carriage of Dangerous Goods by Road (ADR) regulations [94] are applied to govern the flow of DGVs via a road tunnel on a Trans-European Transport Network (TEN-T). This is to avoid the repeat of Mont Blanc [95] and Tauern tunnel incidents. Although the importance of these precautionary measures is inevitable, the undesirable consequences of increased congestion, travel delays, higher fuel consumption and pollution cannot be ignored. With current traffic environments involving conventional vehicles and no connected infrastructure for verification of vehicle's dimensions and goods carriage, the problem pertaining to tunnel checks cannot be resolved. Many previous studies have focused on the concerns of DGVs travelling in the tunnel, but to the best of authors knowledge no study has analysed the impact of their movement surrounding the tunnel using a real-world data. This chapter focuses on traffic flow analysis on the vehicles approaching Dartford-Thurrock River Crossing Tunnel in Kent UK. For the remainder of this thesis the tunnel will be referred as Dartford Crossing tunnel. Following the flow analysis, the study will simulate traffic scenarios based on it with traffic involving conventional vehicles and CAV enabled vehicles to highlight their impact on traffic conditions in a real-world traffic flow simulated model.

With the technological advancements in C-ITS and communications between V2V and V2I, the traffic-related problems could be solved using CAV-F. The usefulness of C-ITS solutions is discussed in previous a study [96] on improving tunnel safety. The report on Stockholm Bypass Tunnel [97] mentions the use of C-ITS solutions to improve traffic and emergency management. Another study [98], looked at scenarios of mixed traffic using CAV to improve traffic capacity but was limited by smaller vehicle counts and using platoons on a single-lane scenario.

## 3.1. Dartford-Thurrock Crossing Tunnel

In UK, there are nine tunnels which are a part of TEN-T network and have been categorised with ADR tunnel codes. The ADR tunnel codes range from A to E, where category A tunnels have no restrictions on the movement of DGVs and category E tunnels having full restriction on the movement of DGVs, except when carrying goods of certain UN categories[1]. Table 2 details the restrictions on each category.

Table 2 ADR tunnel category description [94]

| ADR Category | Description |
|---|---|
| A | No Restrictions on the movement of dangerous goods |
| B | Restrictions to dangerous goods leading to very large explosion |
| C | Restriction to dangerous goods leading to very large explosion, a large explosion, or a large toxic release |
| D | Restriction to dangerous goods leading to very large explosion, a large explosion, a large toxic release, or a large fire |
| E | Restriction to all dangerous goods except for UN2919, UN3291, UN3331, UN3359 and UN3373 |

Based on the above classification, the tunnels in UK are classified as shown in Table 3.

**Table 3** UK road tunnels classification as per ADR tunnel codes since 1 January 2010

| UK Road Tunnels | ADR Category |
|---|---|
| Dartford Thurrock Crossing | C |
| Mersey | D |
| Clyde | D |
| Limehouse | E |
| Rotherhithe | E |
| Blackwall | E |
| East India Dock Road | E |
| Tyne | E |
| Heathrow Airport | Between 0400 and 2300: Category E. At other times: Category C |

[1] **UN2919** – Radioactive Material, Type B(U) Package, non-fissile or fissile-excepted; **UN3291** – Clinical Waste, Unspecified, N.O.S. or (Bio) Medical Waste, N.O.S. or Regulated Medical Waste, N.O.S.; **UN3331** – Radioactive Material, Transported Under Special Arrangement, Fissile; **UN3359** – Fumigated Cargo, Transport unit; **UN3373** – Biological Substances, Category B

To comply with high safety regulations on tunnels, check and allow procedures are deployed to ensure only compliant vehicles could travel through a road tunnel. The above-mentioned tunnels under the category E, do not require check and allow procedures as none of the hazardous goods vehicles are allowed. Any non-compliant vehicles identified crossing the tunnels are fined. The information regarding the restrictions on the on-coming tunnel for DGVs and ALVs are displayed well in advance on roadside, road marking and available gantries. For tunnels under the category C and D, the policing of DGVs is complex as not all but limited vehicle types are restricted and hence vehicles are required to be verified before they enter the tunnel. To enforce check and allow procedures and escorts of vehicles, the toll booths and semi-automated systems, such as installed before Dartford Crossing tunnel, are used in addition to road signs and markings, to monitor and control the flow of vehicles. Using the smart and cooperative intelligent systems, as mentioned by previous studies [99-101], the check and allow could be improved using V2V and V2I technologies. To analyse the impact such V2V and V2I technologies on road traffic using CAV-F transportation, the Dartford-Thurrock Rive Crossing tunnel is identified for research simulations. The tunnel had the toll booths but were removed in 2016 and replaced with traffic signals and barriers which were triggered using multiple vehicles monitoring sensors such as ANPR sensors, orange plate and vehicle dimension reader sensors to control and monitor the movement of vehicles, making the tunnel as only the one in UK with a semi-automated system. With the removal of toll booths, the number of stoppages at tunnel have reduced significantly and are only restricted to escorts procedures for declared DGVs, detection of undeclared and non-compliant vehicle and planned or unplanned maintenance scenarios.

The Dartford Crossing tunnel consists of two bored tunnels and a cabled bridge for vehicles crossing the river Thames in North-East and South-West directions, respectively. The A282 road leading to the Dartford Crossing tunnel is a four-lane road which bifurcates into two-lane roads sections' going into West and East bores of the tunnel. The height of the West Bore is 4.8 meters and 5.0 meters of East Bore. The tunnel is classified as category C tunnels as per ADR [28] regulations which does not allow vehicles where the total net explosive mass of the carriage per transport unit exceeds 5000kg. In addition to this, there are additional specific operating restrictions [102] relating to the passage of DGVs. All the DGVs are required to declare themselves at the designated area named as Kent Marshalling Area (KMA), by exiting the A282 motorway at Junction 1A (except for permitted vehicles as per ADR category C). The dimensions of the vehicles and goods carriage are checked and then the vehicle is either allowed to pass through a tunnel within a defined time frame; escorted through a tunnel as a platoon in isolation of normal road traffic; or sent through an alternative route. For this research, such vehicles will be defined as *'Self-declared vehicles*.'

Further restrictions apply to the physical dimensions of the vehicles to ensure vehicles over the height of 4.8 meters and under 5.0 meters travel through the East Bore only. Any vehicle taller than 5.0 meters must exit the A282 at Junction 1A and navigate through an alternative route. To ensure only compliant vehicles, enter the tunnel, the entrance of the tunnel is equipped with various specialist sensors which continuously monitors and record the road traffic activities on per millisecond basis.

The sensors are installed for each lane on the two separate gantries, situated at 455 meters and 265 meters from the first set of traffic signals and barriers. When a restricted vehicle (a non-compliant vehicle) is detected, the sensors are triggered and the traffic signals and barriers are closed. The vehicle is then extracted from the A282 and navigated to the KMA for inspection. For this research, these non-compliant vehicles will be defined as *'Undeclared vehicles*.'

The traffic modelling in PTV Vissim, is based on Dartford Crossing tunnel with four lane A282 road, two lane Junction 1A exit road, a four-lane roundabout, two and four lane A206 northbound and southbound roads exiting and entering the roundabout, to and from the Dartford Crossing and a KMA. By modelling all the mentioned roads leading to Dartford tunnel, the true impact of the traffic flow could be assessed. The KMA is modelled as a parking lot whereby *'Self-declared vehicles'* will be parked for an average duration of check and allow procedures before re-entering the simulation. Doing so will provide true travel delays of these vehicles.

Figure 5 shows the layout of Dartford Crossing road model in PTV Vissim for experiments.

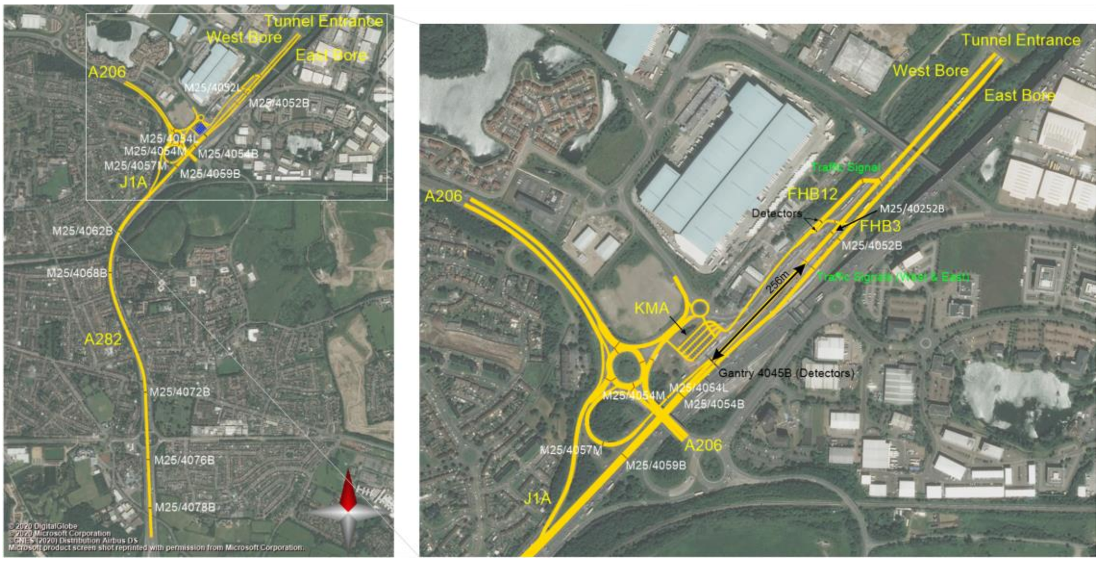

*Figure 5 Traffic simulation model of Dartford Crossing tunnel in PTV Vissim*

## 3.2. Research Methodology

One of the main objectives of this research is to identify the current impact of DGVs and ALVs on the road traffic, congestion, and travel delays near the road tunnel. The study proposes a hypothesis that by reducing or eliminating the tunnel closures at the tunnel by using CAV-F the following would happen:

- Reduction in road congestion
- Improvement in travel times
- Improvement in traffic throughput via the tunnel

By analysing the road traffic conditions for different penetration rates of CAV-Fs driving alongside conventional and CAV enabled vehicles, the study will be able to advocate the *'need'* of CAV-F in improving overall traffic conditions surrounding the tunnel. The focus of this chapter is on:

1. To analyse real-world traffic at Dartford Crossing tunnel and to develop a near-realistic based on the findings. Using this model, the impact of reduction in closure counts and durations would be determined, by simulating the conventional traffic composition only (i.e. without introducing CAV or associated connectivity).
2. To analyse the impact of introducing small proportion CAV-F (replacing conventional DGVs and ALVs) in improving queue lengths and travel time at the Dartford Crossing tunnel. Here, three distinct AV driving behaviours (AV-Cautious, AV-Normal and AV-Aggressive) are compared to analysis the impact.
3. To analyse the impact of CAV-F in improving traffic throughput. This would be determined by replacing all the conventional freight traffic near Dartford Crossing tunnel with CAV-F vehicles, alongside other conventional vehicles such

as cars, buses, motorbike, etc. The hypothesis is that by using CAV-F vehicles the traffic throughput at Dartford Crossing should increase significantly.

The study is only considering normal traffic flow conditions and would not include planned or unplanned incidents or events. The study is only focused on understanding the impact of CAV-F driving behaviours and impact alongside conventional traffic in improving traffic conditions. The V2V and V2I connectivity mechanisms are beyond the scope of this research. This research will be studying the impact of DGVs and ALVs on traffic flow at the Dartford Crossing tunnel. The appropriate permissions have been obtained from the Highways England to use the data for the sole purpose of academic research. The information is stored in a proprietary database.

To setup the traffic simulation experiments for benchmarking and verifying the hypothesis, a careful analysis of the Dartford data was conducted. The benchmarking model has been used to identify traffic patterns for most congested and least congested timeframes along with associated travel delays based on the ratio of traffic volume and number of closures at a given hours. For modelling the simulated Dartford Crossing tunnel scenarios as close to real-world, the following parameters are identified:

- Average Hourly traffic flow entering tunnel for various vehicle compositions
- Average vehicle flow percentages to and from on A282, J1A, A206 roads and KMA
- Average Hourly Total tunnel closure duration
- Average extraction closure duration
- Average escort closure duration
- Average missed detection closure duration
- Average KMA parking duration

### 3.2.1. Traffic Composition and Flow Percentages

One of the crucial information obtained from the dataset was the hourly frequency of vehicles approaching the tunnel which were recorded and classified as per ECTN28 [103] vehicle categories. By analysing the data, it was determined that on average 77,781 vehicles daily or 3,246 vehicles hourly, crossed the tunnel between 1$^{st}$ March 2017 and 14th February 2018. These figures closely aligned with the report published by DfT in 2009 [104]. The detailed list of vehicle classification as per ECTN28 is stated in Table 4.

Table 4 ECTN28 Vehicle classification with hourly vehicle count analysis per category basis

| ECTN 28 | Name | Description | Avg. Vehicle Count % |
|---|---|---|---|
| **000** | Unknown | Detectable, but not classifiable vehicle. | 0.19% |
| **210** | Car | Car (up to 9 seats, <=3.5t total weight). | 66.81% |
| **211** | Car with trailer | Car (up to 9 seats, <=3.5t total weight). | 0.62% |
| **310** | Van | Van with tapered front, superstructure at least as high as cabin (including mini trucks and moving van, 2.8t to 3.5t weight). | 10.89% |
| **311** | Van with trailer | Van with trailer (2.8t to 3.5t weight). | 0.17% |
| **320** | Pickup Van | Pickup-style van with no or small loading. (Cabin in the front, no superstructure, weight <=3.5t). | 2.06% |
| **321** | Pickup Van with trailer | Pickup-style van with no or small loading with trailer. (Cabin in the front, no superstructure, weight <3.5t). | 0.06% |
| **330** | Caravan | Motorhome. (Cubical size, rooftop with extension (e.g. bunk), weight <=3.5t). | 0.09% |
| **331** | Caravan with trailer | Motorhome with trailer. (Cubical size, rooftop with extension (e.g. bunk), weight <=3.5t). | 0.00% |
| **340** | Semitrailer van | Semi-trailer van (weight <3.5t). | 0.02% |
| **410** | Truck | Truck with superstructure (up to 12m length, weight >3.5t). | 2.56% |
| **411** | Truck with trailer | Truck with superstructure and trailer. (Up to 18.75m length, weight >3.5t). | 0.56% |
| **420** | Dumper truck | Dumper truck with empty or nearly empty dumper. (Up to 12m length, weight >3.5t). | 0.24% |
| **421** | Dumper truck with trailer | Dumper truck with empty or nearly empty dumper, with trailer. (Up to 18.75m length, weight >3.5t). | 0.00% |
| **430** | Tank truck | Tank track for transport of fluids. (oval cross-section, up to 12m length, weight > 3.5t) | 0.22% |
| **431** | Tank truck with trailer | Tank track for transport of fluids, with trailer. (oval cross-section, up to 18.75m length, weight > 3.5t) | 0.01% |
| **440** | Low loaded truck | Truck without superstructure or with low cargo (cargo lower than cabin, up to 12m length, weight > 3.5t) | 1.07% |
| **441** | Low loaded truck with trailer | Truck without superstructure or with low cargo, with trailer (cargo lower than cabin, up to 18.75m length, weight > 3.5t) | 0.08% |
| **450** | Vehicle transporter | Vehicle transporter truck, loaded, with trailer (2 loading platforms, up to 21.5 m length, weight > 3.5t) | 0.08% |
| **451** | Vehicle transporter | Vehicle transporter, empty, with trailer (2 loading platforms, up to 21.5 m length, weight > 3.5t) | 0.02% |
| **510** | Semitrailer truck | Semi-trailer truck (loaded, up to 16.5m length, weight > 3.5t) | 11.15% |
| **520** | Semitrailer dumper truck | Semi-trailer dumper truck with empty or nearly empty dumper. (up to 16.5m length, weight > 3.5t) | 0.07% |
| **530** | Semitrailer tank truck | Semi-trailer tank truck (oval cross-section, up to 16.5m length, weight > 3.5t) | 0.68% |
| **540** | Low loaded semitrailer truck | Semi-trailer truck unloaded or with low loading (up to 16.5m length, weight > 3.5t) | 0.68% |
| **590** | Tractor truck | Semi-trailer's tractor truck, without semi-trailer. | 0.24% |
| **610** | Bus | Bus for transport of a bigger number of people. (coach, overland bus, > 9 seats) | 0.46% |
| **611** | Bus with trailer | Bus for transport of a larger number of people, with trailer. (coach, overland bus, > 9 seats) | 0.01% |

However, the vehicle count obtained from Dartford Crossing data only provided the information about the traffic flow on A282 four-lane road leading to East and West bores of the tunnel, slip road merging into A282 prior to the tunnel and vehicles entering and exiting the KMA.

The traffic count for Junction 1A (J1A) were obtained from the Highways England WebTRIS website [105] and from Motorway Incident Detection and Automatic Signalling (MIDAS) [106, 107] site located at M25/4059L (GPS Ref: 555670E; 174832N) under the Open Government License. The traffic count for the A206 eastbound road, was obtained from the DfT Road traffic statistics [108], Manual count point number 99906 – A206 (GPS Ref: 554000E, 175670N). The data obtained was measured for a specific date 15$^{th}$ May 2017 between 0700 and 1800 hours.

For the traffic simulation in PTV Vissim, the above vehicle categories are grouped into three:

- *Cars* – includes categories between ECTN28 210 to 340.
- *HGVs* – includes categories between ECTN28 410 to 590.
- *Buses* – includes categories ECTN28 610 and 611

Based on the grouping it was observed that *Cars* dominated the traffic volume by 80.73% followed by *HGVs* at 17.64% and *Buses* at 0.48%. The grouping of the categories is based on the similarities based on acceleration-deceleration functions, and car-following and lane changing behaviours of different vehicle types.

Three further sub-categories of HGVs vehicle types w defined based on their driving pattern at the tunnel, irrespective of ECTN28 classification. The closures at the tunnel are dependent on these categories. The categories are:

- *Declared* – compliant DGVs or ALVs vehicles travelling to KMA for check and allow procedures, which are either escorted into the tunnel, re-routed via A282 into the tunnel or their passage is restricted and are diverted to an alternative route.
- *Undeclared* – non-compliant DGVs or ALVs vehicles which fail to report at KMA and are detected by sensors on A282, triggering tunnel closure.
- *Missed Detected* – non-compliant DGVs or ALVs which are detected on A282 and triggers road closure are missed for extraction due to human error.

To correctly identify the traffic flow parameters for the simulations and to replicate the real-world scenarios accurately, the study has statistically analysed the Annual Average Daily

Traffic (AADT) and Annual Average Hourly Traffic (AAHT) flows at Dartford Crossing tunnel including at KMA for *Cars* and *HGVs* vehicle categories. The analysis was identified into three distinct categories as, *'Weekdays'* (from Monday to Thursday), *'Friday'* and *'Weekends'*. The *Friday* was identified as its own category because by analysing the annual data for Dartford Crossing tunnel it was observed that for most of the year the traffic flow on *Friday* was distinguishably different from *Weekdays* and *Weekends*.

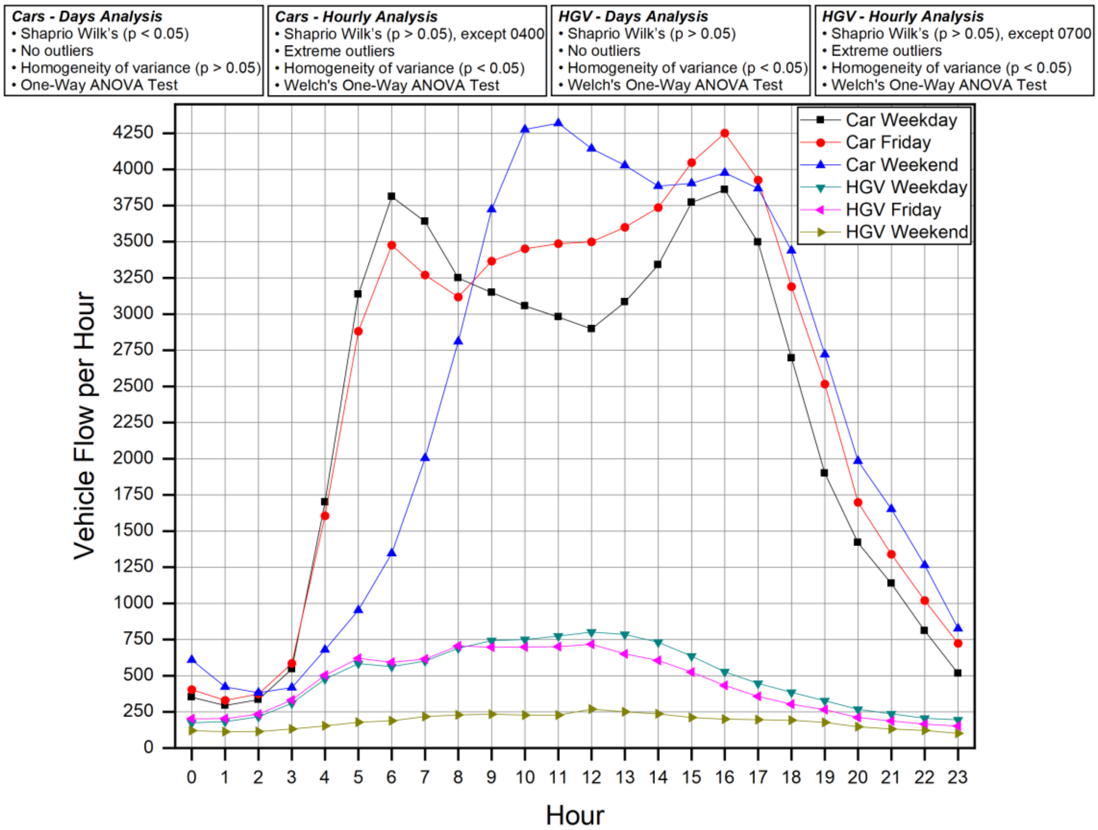

*Figure 6 AAHT flow of Cars and HGVs vehicle categories traveling via Dartford Tunnel*

In Figure 6 it could be noted that for *Cars* the flow peaked in mornings and late afternoons for *Weekdays* and *Friday* categories. In contrast, the flow of *Cars* on *Weekends* started to rise between 0700 - 0800 hours instead of 0400 - 0500 hours and remained high till 1700 hours, followed by steep drop, in line with other two categories. For *HGVs* the flow was observed to be higher during the mid-day for all three categories, levelling off at night.

The One-Way ANOVA [109] was conducted to determine if the AAHT flows for *Cars* and *HGVs* were significantly different between *Weekdays*, *Friday* and *Weekends*. The AAHT of *Cars* decreased from *Friday* (*Sample Size* (*N*) *= 24, mean (M) = 2496, Standard Deviation (SD) = 1349*) to *Weekdays* (*N = 24, M = 2402, SD = 1362*) to *Weekdays* (*N = 24, M = 2299, SD = 1293*), in that order. The AAHT of *HGVs* decreased from *Weekdays* (*N = 24, M = 484, SD = 225*) to *Friday* (*N = 24, M = 445, SD = 210*) to *Weekends* (*N = 24, M = 182, SD = 50*), in that order. It could be observed that the traffic for all the categories varied significantly during the day, except for *HGVs* AAHT over the *Weekends*. As the condition of homogeneity is met for *Cars*, One-Way ANOVA with Tukey post-hoc test was conducted. The AAHT for *Cars* was not significantly different between the categories, *F-Distribution (F)(2,69) = 0.122*, *p = 0.885*, *partial eta squared* $\eta^2 = 0.004$. For *HGVs*, as the condition for homogeneity was violated for all three categories, Welch's One-Way ANOVA with Games-Howell post-hoc test was conducted. The AAHT for *HGVs* was significantly different between the categories, Welch's $F(2,33.64) = 35.82$, $p < 0.05$. Games-Howell post hoc analysis showed that the *HGVs* AAHT flows on *Weekdays* and *Friday* were significantly similar ($p = 0.809$) and was significantly different with *Weekends* ($p < 0.05$) for both the categories.

The hourly AAHT for *Cars* was compared for the traffic flows on *Weekdays*, *Friday* and *Weekends* categories and a Welch's One-Way ANOVA with Games-Howell post-hoc test was conducted. The AAHT for *Cars* was significantly different between the categories, Welch's *Weekdays* $F(23, 94.81) = 798.90$, $p < 0.05$, *Friday* $F(23, 95.04) = 712.12$, $p < 0.05$ and *Weekends* $F(23, 95.20) = 721.45$, $p < 0.05$. Games-Howell post hoc analysis showed that overall, the flow of traffic between 2200-0300 hours was statistically similar ($p > 0.05$) and traffic flow between 0500-1800 hours was statistically similar ($p > 0.05$) for all the three categories.

The hourly AVTT for *HGVs Cars* was compared for the traffic flows on *Weekdays*, *Friday* and *Weekends* categories and a Welch's One-Way ANOVA with Games-Howell post-hoc test was conducted. The AAHT for *HGVs* was significantly different between the categories, Welch's *Weekdays* $F(23, 95.47) = 293.03$, $p < 0.05$, *Friday* $F(23, 95.45) = 267.11$, $p < 0.05$ and *Weekends* $F(23, 115.38)$, $p < 0.005$. Games-Howell post hoc analysis showed that on *Weekdays* and *Friday* the flow of *HGVs* between 2000-0300 hours and the flow between 0700 and 1500 hour was statistically similar ($p > 0.05$). The traffic between the 0400 to 0700 hours and from 1500 to 1700 hours was similar ($p > 0.05$). For *HGVs* on *Weekends* the flow was statistically similar between 2100 and 0200 hours but at 0300 hours the traffic flow was observed to be statistically similar from 1700 hours instead of 2100 hours ($p > 0.05$). Also, the flow at 0400 hours was statistically similar to flow between 0300 and 0700 hours and 1500 and 1900 hours ($p > 0.05$). The flow between 0800 and 1500 hours was observed to be similar ($p > 0.05$).

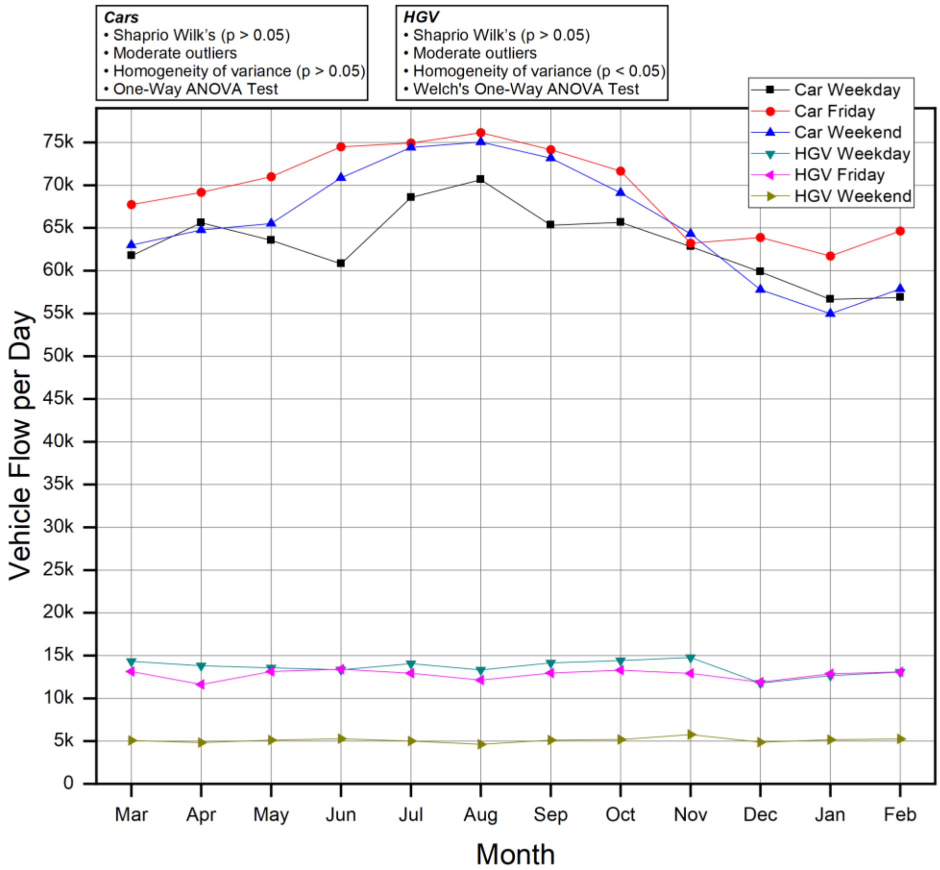


*Figure 7 AAMT flow of Cars and HGVs at Dartford Crossing tunnel*

Figure 7 shows that the flow curve for *Cars* followed a unimodal normal distribution where the traffic tends to increase during summer, between May and September, and reduce during winters, between October and Jan, followed by a continual rise from January. On contrary, the flow of *HGVs* appears to be linear, with a drop in the traffic flow during December. This drop in December is associated with a significantly low traffic on 25$^{th}$ December until 2$^{nd}$ January.

A One-Way ANOVA was used to compare the flow of AADT between the months for *Cars* and *HGVs* vehicle types for *Weekdays*, *Friday*, and *Weekends*. A One-Way ANOVA with Tukey's post-hoc test was conducted for the AADT for *Cars*. Significantly difference between the months for *Weekdays* $F(11, 190) = 7.95$, $p < 0.05$, *Friday* $F(11, 38) = 6.34$, $p < 0.05$ and *Weekends* $F(11, 88) = 22.54$, $p < 0.05$ were observed. Tukey's post-hoc analysis showed that the AADT on *Weekdays* in January was statistically similar to the flow in months between November and March ($p > 0.05$). In February, the flow was similar to all the months except for July and August, and for March the flow was similar to all except August. For April to June and November the flows were statistically similar to all the months. The flow in July and August was similar to all the months except for flow between December and February. And for September and October the AADT of *Cars* on *Weekdays* was similar to all the months except for January. By assessing the AADT of *Cars* on *Friday* using Tukey's post hoc testing, the AADT for all the months was statistically similar ($p > 0.05$), expect for January where the AADT was not statistically similar to months between June and September ($p < 0.05$). For AADT of *Cars* on *Weekends* as assessed using Tukey's post hoc, it was observed that the flow during June and October were statistically similar and flow between November and May was statistically similar ($p > 0.05$).

A Welch's One-Way ANOVA was conducted for the AADT for *HGVs* and it was observed to be statistically similar for all the three categories and between all the months, *Weekdays* $F(11, 190) = 2.19$, $p = 0.016$, *Friday* $F(11, 38) = 0.57$, $p = 0.835$ and *Weekends* $F(11, 88) = 1.15$, $p = 0.334$. From the analysis it was noted that although the AAHT between the *Weekdays*, *Friday* and *Weekends* categories was homogeneous, comparison of flow between the hours and AADT between months showed variations.

### 3.2.2. Kent Marshalling Area Vehicles

The KMA is a designated zone prior to the tunnel where all the DGVs and ALVs must assemble before crossing the tunnel. The vehicles are then checked and classified based on their carriage and dimensions. These are labelled as *'Declared'* vehicles. The vehicles classified at KMA are either sent back to the A282 road, being compliant; escorted separately as carrying potentially hazardous goods or are sent via an alternative route for being non-compliant. The count of vehicles entering the KMA and duration spent at KMA was obtained from the data. This information was used in the model to accurately measure the vehicle delays and for simulating realistic escorting scenarios of vehicles. Figure 8 shows the AADT entering the KMA over the *Weekdays*, *Friday,* and *Weekends*.

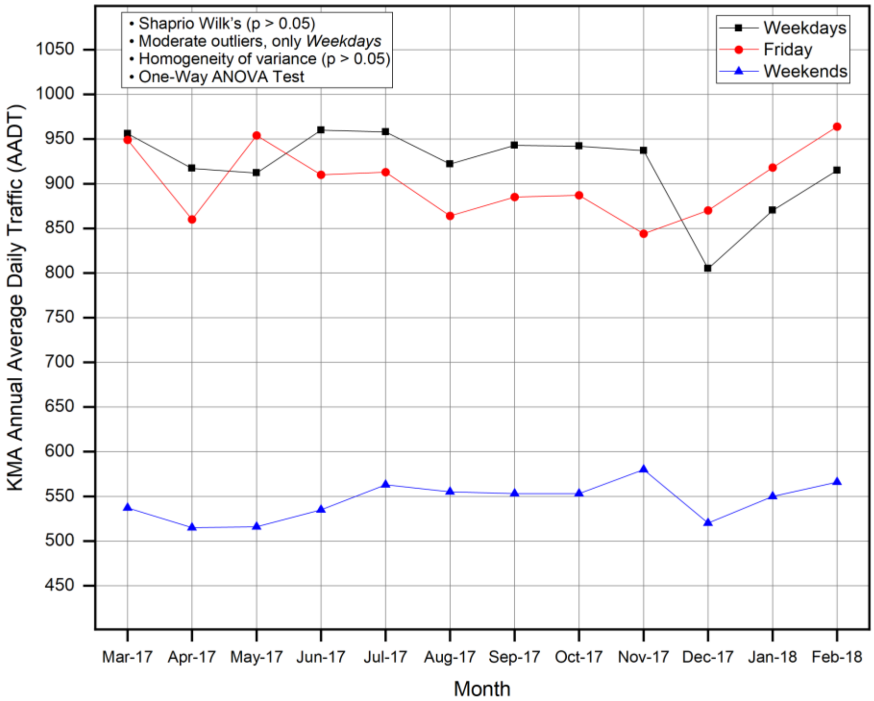


*Figure 8 AADT flow of Declared vehicles entering KMA*

A One-Way ANOVA with Tukey's post-hoc test was conducted to determine if AADT of *Declared* vehicles into KMA was significantly different between *Weekdays*, *Friday*, and *Weekends*. The flow between the categories was statistically significantly different $F(2, 33) = 403.19, p < 0.05$. The post-hoc testing showed that the AADT for *Weekdays* and *Friday* was statistically similar ($p = 0.533$) but rest all other combinations were different.

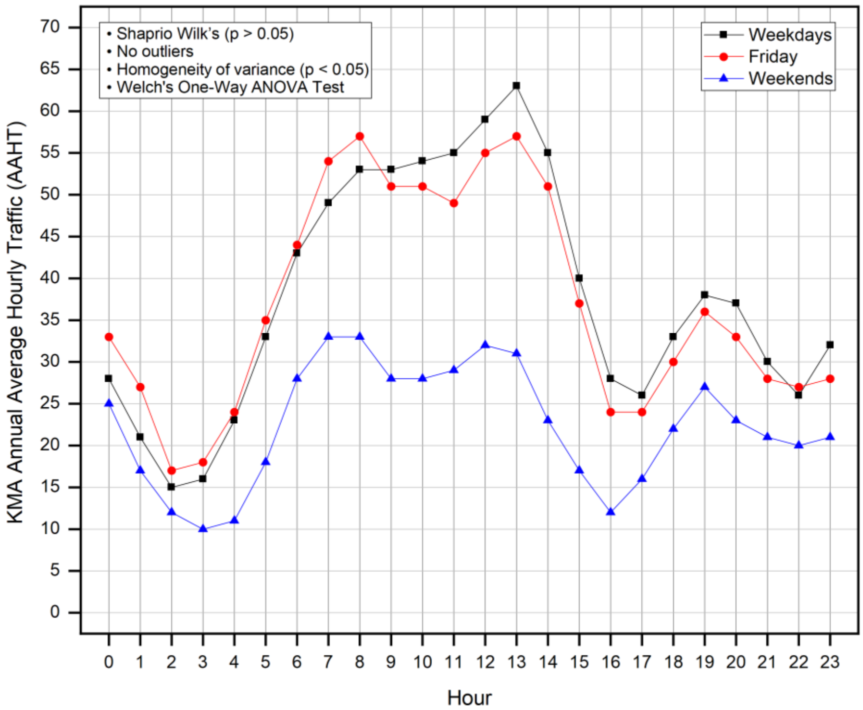


*Figure 9 AAHT Flow of Declared vehicles entering KMA*

A Welch's One-Way ANOVA with Game-Howell post-hoc test showed that the flow of *Declared* vehicles in KMA on an hourly basis was statistically significantly different between the three categories Welch's $F(2, 42.85) = 17.96, p < 0.05$. The Games-Howell post-hoc testing showed that AAHT flow between *Weekdays* and *Friday* was statistically similar ($p = 0.998$).

Another statistic used was the KMA *'parking times'* which reflects the time spent by *Declared* vehicles for check and allow procedures. From the data, the Annual Average Hourly Duration (AAHD) was approximately 30 minutes, with minimum duration observed at 1 minute 45 seconds, probably for a vehicle entering the KMA by mistake and exiting, and the maximum duration at approximately 10 hours, probably time taken to obtain valid permit overnight or a system error). The experiments in the study used the flow counts and duration for KMA parameters as an average of the simulated hour.

### 3.2.3. Tunnel Closures

To police the traffic flow at the Dartford Crossing tunnels, the check and allow procedures for DGVs and ALVs are made mandatory. By simulating the hourly closure counts for the average duration, the traffic simulation would be able to realistically determine the impact of these closures on traffic flows, queues, and delays. The counts and duration of emergency closures and planned closures are not included in simulation because the total impact of emergency and planned closures is low with approximately 6% of total closures. Also, the planned closures are limited to schedule during the night-time when the traffic flow is minimum. From the data it could be observed that for majority of the time, planned closures were between 21:30 hrs and 05:00 hours. During this period, the average flow of vehicles was approximately 75% less than that of peak hours. The study, also, does not include the unplanned closures due to traffic incidents and accidents, and ramp metering scenarios.

For modelling purposes, the Dartford Crossing data would be able to provide information regarding the stoppages associated with the movement of DGVs and ALVs. The closure parameters used in the simulation are grouped into three distinct closure categories:

- Closure for escorting of *Declared* vehicles from the KMA, referred as *'Release'*.
- Closure for *Undeclared* vehicles on the A282 with successful extraction of the vehicle to KMA for checking and possible penalising is referred to as *'Extraction'*.
- Closure for *Undeclared* vehicles on the A282 with unsuccessful extraction causing vehicle to enter the tunnel without any checks is referred as *'Missed Detect'*.

The identified closure categories are also exact representation of real-world closure scenarios at the Dartford Crossing tunnel.

Figure 10 the Annual Average Daily Tunnel Closures (AADTC) for *Extraction*, *Release* and *Missed Detect* closure categories.

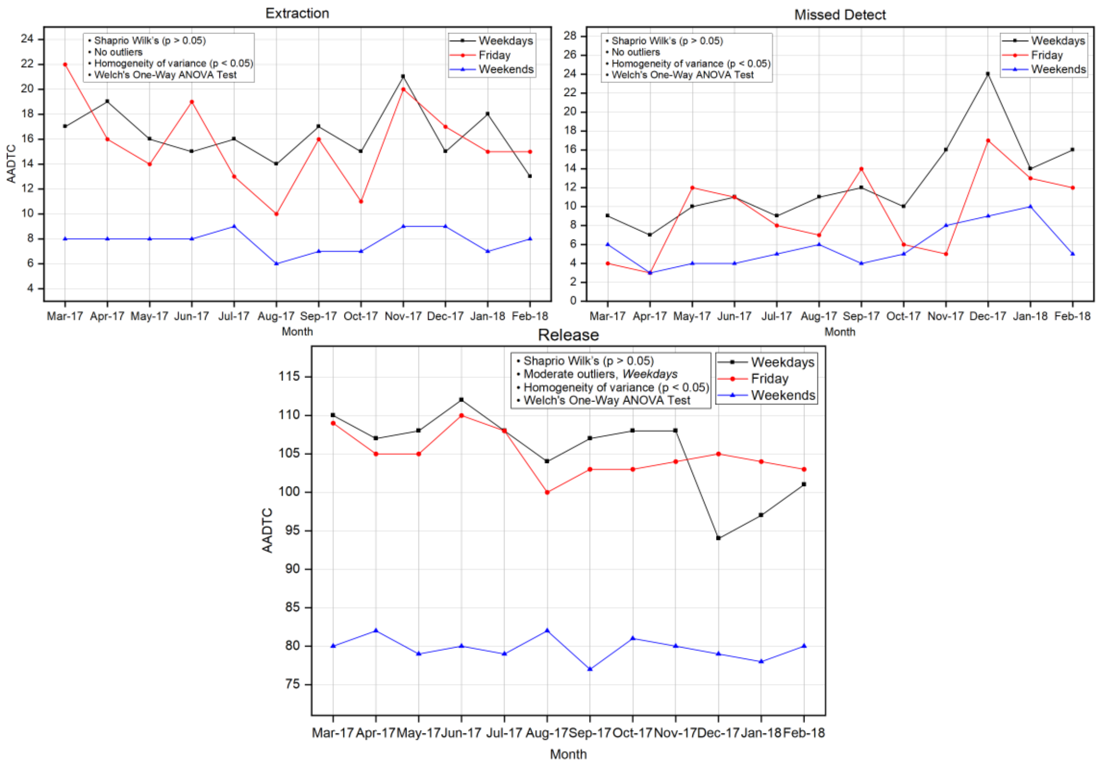


*Figure 10 AADTC for Extractions, Release and Missed Detect at Dartford Crossing tunnel*

A Welch's One-Way ANOVA with Games-Howell post-hoc test was conducted and it showed that AADTC for all three categories were statistically significantly different, *Extraction* $F(2, 42.99) = 4.28$, $p = 0.020$, *Release* $F(2, 45.50) = 17.39$, $p < 0.005$ and *Missed Detect* $F(2, 44.10) = 8.03$, $p = 0.001$. The Games-Howell post-hoc test revealed that the *Extractions* on *Weekdays* ($N = 24$, $M = 1.41$, $SD = 0.50$) was statistically similar to *Friday* ($N = 24$, $M = 1.25$, $SD = 0.44$) ($p = 0.449$) but was statistically different to *Weekends* ($N = 24$, $M = 1.08$, $SD = 0.28$) ($p = 0.020$). However, the *Extractions* on *Friday* was statistically significantly similar to *Weekdays* ($p = 0.449$) and *Weekends* ($p = 0.277$). The post-hoc test for *Release* category showed that the AAHTC was only statistically similar for *Weekdays* ($N = 24$, $M = 4.50$, $SD = 0.88$) and *Friday* ($N = 24$, $M = 4.29$, $SD = 0.80$) ($p = 0.673$), but not with *Weekends* ($N = 24$, $M = 3.29$, $SD = 0.69$) ($p < 0.005$). The post-hoc test for *Missed Detect* category showed that the AAHTC was only statistically similar for *Friday* ($N = 24$, $M = 1.54$, $SD = 0.50$) and *Weekends* ($N = 24$, $M = 1.41$, $SD = 0.50$) ($p = 0.671$), but not with *Weekdays* ($N = 24$, $M = 1.87$, $SD = 0.33$) ($p < 0.05$).

Figure 11 shows the Annual Average Hourly Tunnel Closures (AAHTC) for *Extraction*, *Release* and *Missed Detect* closure categories.

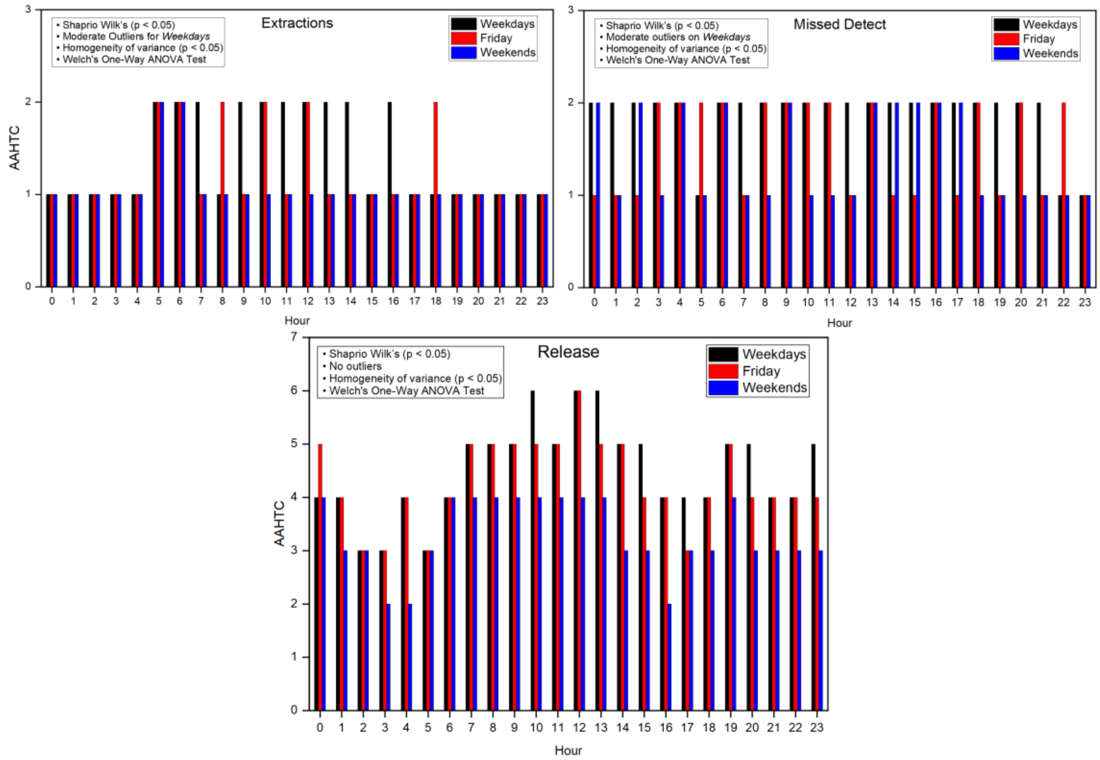


*Figure 11 AAHTC for Extractions, Release and Missed Detect at Dartford Crossing tunnel*

The AAHTC was analysed using a Welch's One-Way ANOVA with Game-Howell's post-hoc test. The closures were statistically significantly different for *Extractions* $F(2, 42.99) = 4.28$, $p = 0.20$, *Release* $F(2, 45.50) = 17.39$, $p < 0.0005$ and *Missed Detect* $F(2, 44.10) = 8.03$, $p = 0.001$. Games Howell's post-hoc test revealed that for *Extraction* category the closures on *Weekdays* ($N = 24$, $M = 1.41$, $SD = 0.50$) were statistically similar to closures on *Friday* ($N = 24$, $M = 1.25$, $SD = 0.44$) ($p = 0.449$) but not with the closures on the *Weekends* ($N = 24$, $M = 1.25$, $SD = 0.28$) ($p < 0.05$). Also, the *Extractions* on *Friday* were statistically similar to that of *Weekends* ($p = 0.277$). For *Release* category, Games-Howell test revealed that only the closure on *Weekdays* ($N = 24$, $M = 4.50$, $SD = 0.88$) were statistically similar to *Friday* ($N = 24$, $M = 4.29$, $SD = 0.69$) ($p = 0.637$) and for all other combinations with *Weekends* ($N = 24$, $M = 3.29$, $SD = 0.94$), the closures were statistically significantly different ($p < 0.05$). For *Missed Detect* category, Game-Howell's test showed that the closures between *Friday* ($N = 24$, $M = 1.54$, $SD = 0.50$) and *Weekends* ($N = 24$, $M = 1.41$, $SD = 0.50$) were statistically significantly similar ($p = 0.671$) and all other combinations with closures on *Weekdays* ($N = 24$, $M = 1.87$, $SD = 0.33$) were statistically different ($p < 0.05$).

By analysing the AAHTC, it was observed that number of *Releases* was approximately 22.98% higher than the other two closure categories. The daily hourly closure counts showed that *Releases* were approximately 39.61% higher than *Extractions* and *Missed Detect* closures. It was noted that number closures were directly proportional to the flow of *HGVs* traffic flow. By comparing the figures from Dartford Crossing tunnel following the removal of toll booths in 2016 to the figures from Dartford Crossing tunnel prior to 2016, a notable reduction in the vehicle stoppages were observed. Assuming approximately all the vehicles approaching the toll booths of Dartford Crossing tunnel were stopped, then on average 3,245 vehicle/hour [110] were stopped. With new semi-automated system and only a fraction of closures per hour, approximately 6, were observed, substantially increasing the traffic flow at the tunnel.

Another useful statistic determined from the tunnel closures was the duration of each closure category. Table 5 shows the hourly average counts, duration for individual three categories and total closure duration per hour.

Table 5 Average Hourly counts and durations of *Extractions*, *Releases* and *Missed Detects*

| Hr | Extraction | Extraction Duration | Release | Release Duration | Missed Detect | Missed Detect Duration | Total Hourly Closure Duration |
|---|---|---|---|---|---|---|---|
| 0 | 1 | 00:02:31 | 4 | 00:01:31 | 1 | 00:01:03 | 00:09:38 |
| 1 | 1 | 00:02:51 | 4 | 00:01:31 | 1 | 00:01:40 | 00:10:35 |
| 2 | 1 | 00:03:07 | 3 | 00:01:26 | 2 | 00:00:43 | 00:08:51 |
| 3 | 1 | 00:03:46 | 3 | 00:01:15 | 2 | 00:01:16 | 00:10:03 |
| 4 | 1 | 00:03:15 | 3 | 00:01:06 | 2 | 00:02:28 | 00:11:29 |
| 5 | 2 | 00:02:57 | 3 | 00:01:04 | 1 | 00:01:12 | 00:10:18 |
| 6 | 2 | 00:02:58 | 4 | 00:01:10 | 2 | 00:01:21 | 00:13:18 |
| 7 | 2 | 00:03:04 | 5 | 00:01:11 | 1 | 00:01:24 | 00:13:27 |
| 8 | 1 | 00:02:47 | 5 | 00:01:12 | 2 | 00:01:35 | 00:11:57 |
| 9 | 2 | 00:03:08 | 5 | 00:01:11 | 2 | 00:01:14 | 00:14:39 |
| 10 | 2 | 00:03:23 | 5 | 00:01:13 | 2 | 00:01:20 | 00:15:31 |
| 11 | 1 | 00:03:12 | 5 | 00:01:13 | 2 | 00:01:30 | 00:12:17 |
| 12 | 2 | 00:03:13 | 5 | 00:01:13 | 2 | 00:01:20 | 00:15:11 |
| 13 | 2 | 00:03:16 | 5 | 00:01:16 | 2 | 00:01:39 | 00:16:10 |
| 14 | 1 | 00:03:18 | 5 | 00:01:15 | 2 | 00:01:15 | 00:12:03 |
| 15 | 1 | 00:03:16 | 4 | 00:01:11 | 2 | 00:01:24 | 00:10:48 |
| 16 | 1 | 00:03:23 | 3 | 00:01:09 | 2 | 00:01:26 | 00:09:42 |
| 17 | 1 | 00:03:09 | 3 | 00:01:09 | 2 | 00:01:25 | 00:09:26 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 18 | 1 | 00:03:07 | 4 | 00:01:10 | 2 | 00:01:26 | 00:10:39 |
| 19 | 1 | 00:03:04 | 4 | 00:01:14 | 2 | 00:01:28 | 00:10:56 |
| 20 | 1 | 00:03:05 | 4 | 00:01:18 | 2 | 00:01:30 | 00:11:17 |
| 21 | 1 | 00:02:57 | 4 | 00:01:30 | 2 | 00:01:11 | 00:11:19 |
| 22 | 1 | 00:02:55 | 4 | 00:01:35 | 1 | 00:00:46 | 00:10:01 |
| 23 | 1 | 00:03:12 | 4 | 00:01:32 | 1 | 00:00:29 | 00:09:49 |

Although the traffic flow and number of vehicles being stopped at the tunnel has reduced significantly, from the data it could it be seen that on average minimum ~9 minutes to maximum ~16 minutes closures are required throughout the day to deal with *Declared* and *Un-declared* DGVs and ALVs vehicles, totalling of approximately 4 hours 40 minutes closures a day, on average. Moreover, by adding the AAHTC averages for all three closures categories the minimum number of closures observed were 6 and with a maximum 9 per hour. By observing the closure frequency, it could be noted that on an average 4 closures were conducted hourly throughout the day. Figure 12 shows the frequency of distinct hourly closures over one year.

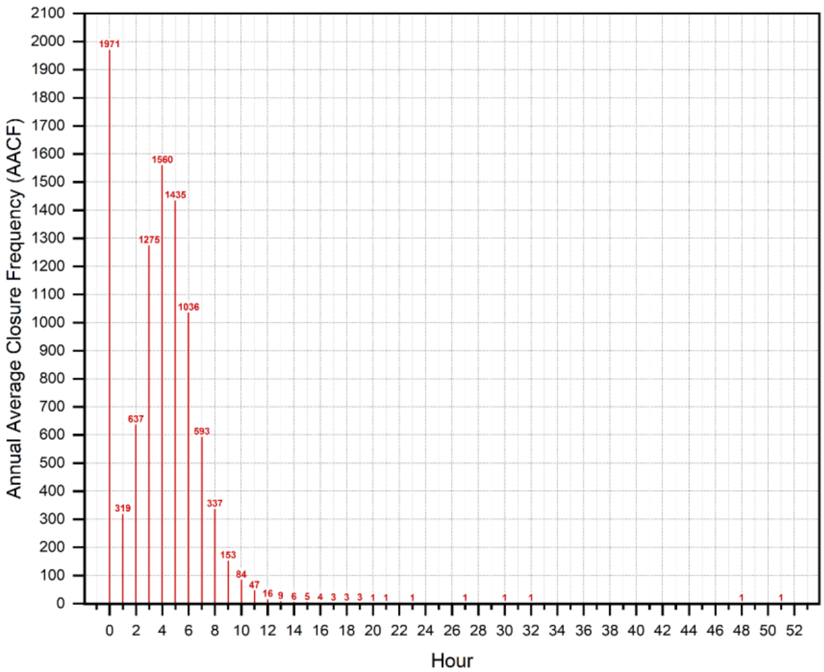


*Figure 12 Annual frequency plot of average hourly closure counts*

It is noted that zero closure count topped at 1971 followed by the count of 4 hourly closures at 1560 counts. By further analysis it was determined that 99.54% of these zero closures were during 2100 hrs and 0400 hrs and only 43 occurrences were distributed randomly outside these hours in one-year duration. It should be noted that planned tunnel closures were often between 2100 hrs and 0500 hrs and thus it could be concluded that zero closures are not significantly frequent.

Hence, by using average four closures per hour and associated average duration, the average daily closure duration was calculated to be approximately 2 hours (excluding maintenance closures). Using these closure counts and durations as a benchmark the simulation experiments will examine and try to find the optimal closure count with lowest closure duration where the traffic flow and travel times will improve. The study hypothesises that by eliminating the closures with CAV-F implementation will be the most optimal solution alongside existing vehicles and future CAV enabled traffic.

### 3.2.4. Closures Modelling with Traffic Signals

To model the tunnel closures, traffic signals were modelled using the PTV Vissim's Visual Vehicle Actuated Program (VisVAP). For simulating the closures for the *Extraction* and *Missed Detect* vehicles, sets of traffic signals on A282 East and West bores were positioned, and for *Releases* from KMA sets of two traffic signals on FHB lane 1 and lane 2, and FHB lane 3, were positioned. The positioning of these traffic signals was determined as per real-world road layout observed via Google Maps for Dartford Crossing tunnel. To trigger the traffic signals on East and West bores, mimicking the real-world, Vissim's detector components are placed at the distance of 265 meters, as per actual distance to the nearest gantry (4045B) from traffic signals on A282.

When the *Missed Detect* vehicle was detected by the detector, the close sequence for the traffic signals pertaining to lane on which the vehicle was detected was triggered. The timeout set for the traffic signal to go from red to green was calculated as below:

$$t = \frac{d}{s} - c \tag{1}$$

where, $t$ = time to close the traffic signals, in seconds; $d$ = distance between the sensor and traffic signals, in meters; $s$ = current speed of the detected vehicle, in meters; c = constant signal transition time from red to green state.

In the experiments the $d$ is 256 meters, $s$ is obtained by the Vissim's detector component which monitors the speed of vehicles as they pass over it, and $c$ was set to 6 seconds (sum of 3 seconds between each transition of red to amber, amber to green and vice-versa signal sequences). For the escort of *Declared* vehicles via FHB, the sets of traffic signals along with associated detectors were defined on Lanes 1, 2 and 3. Lanes 1 and 2 shared a set of traffic signals and release vehicles in West bore. Lane 3 of FHB had a separate traffic signal which releases vehicles in East bore. The time sequence for FHBs traffic signals was immediate and as the detection of *Declared* vehicle was observed, traffic signal(s) for associated lane was set to green. For the simplicity of simulating *Release* scenarios, each *Declared* vehicle detection is assumed to be a set of escorted vehicles. The hourly closure counts, and durations were determined from Dartford Crossing data, as noted in Table 5.

As an initial state, traffic signals on A282 were set to green and traffic signals on FHBs were set to red. To identify and simulate realistic tunnel closure behaviour using traffic signals, the durations for each categorised detection in the experiments, were set to average closure duration for the given hour. To ensure the correct sequence and behaviour of traffic signals the following rules are implemented using VisVAP for traffic signals:

- For detections on West bore, only West bore traffic signals are closed.
- For detections on East bore, both East and West bores traffic signals are closed.
- For East bore detection, West bore traffic signals are closed for extra 75 seconds (average obtained from the data)
- For detections on FHB Lanes 1 and 2, West bore traffic signals are also closed.
- For detections on FHB Lanes 2, both East and West bores traffic signals are closed
- If detection observed for already closed traffic signal, the running closure duration is incremented by average closure category duration.

## 3.3. Simulation Model vs Real-world MIDAS Data

Establishing the accuracy of the PTV Vissim traffic model simulations is a very crucial step. Comparison with an independent real-world MIDAS dataset was conducted to ensure its validity. The average traffic flow per minute for hourly *Simulated* and *Real-world* groups was statistically analysed. The hypothesis is that the vehicle flow between *Simulated* and *Real-world* groups are statistically similar. From the Dartford Crossing data, six hours are identified on a rule that selected hours should include at least one of each three closure events to the test worst case closure scenarios. The closure durations used in simulations are averaged for the closures in the given hour. The identified hours are, 0000hrs on 03rd May 2017, 0600hrs on 15th November 2017, 0900hrs on 18th December 2017, 1400hrs on 26th January 2018, 1600hrs on 01st February 2018 and 1800hrs on 07th March 2017. The traffic flow from three specific MIDAS locations is observed. The locations are M25/4059B (GPS Ref: 555823;174985); M25/4054L (West bore, GPS Ref: 555952;175143) & M25/4054B (East

Bore, GPS Ref: 555962;175137); and M25/4052L (GPS Ref: 556202;175425) & M25/4052B (GPS Ref: 556217;175412) [111]. These location points are chosen because MIDAS loops at M25/4059B and M25/4054 are after the J1A and before N06 merger. The loop at M25/4052 are after the traffic signals on A282 and prior to FHB roads mergers. Hence it accounts for the traffic coming from N06. The traffic flow of *Release* vehicles via FHB roads is not accounted as vehicles in simulated Release scenario are not true representative of real-world flow. The real-world traffic flow from three MIDAS locations is averaged and compared against the averaged six random simulation runs results, obtained from PTV Vissim's '*Data Collection Points*' positioned to mimic MIDAS loops at identified locations. As the simulation model is used for controlled experiment for three closure scenarios, hence to adjust the traffic flow for unaccounted planned or unplanned events and accidents; and approximated diverted and merged traffic at A282 junctions, the relative difference ($d_r$) [112] is calculated between *Real-World* and *Simulated* groups, and is subtracted from averaged simulated results. Relative difference ($d_r$) is calculated as:

$$d_r = \frac{|\Delta|}{\left(\frac{(x+y)}{2}\right)} \quad (2)$$

where, $x = \sum_{i=0}^{n} \bar{x}_{real\text{-}world}$, $y = \sum_{i=0}^{n} \bar{y}_{simulated}$, $|\Delta| = |x - y|$, $n$ = *Observation resolution.*

The values for $\bar{x}_{real-world}$ and $\bar{y}_{simulated}$ are calculated based on the data provided and detailed in Appendix 1.

Using (2), the $\%\, d_r$ between the two averaged traffic flow distributions is calculated at 0.52%. By adjusting the flow of simulated group with calculated value and analysing for normality using the Shapiro-Wilk's test, it was observed that flow distributions were not normal as shown in Table 6.

**Table 6** Normality comparison AAH traffic flow

| Category | Shapiro-Wilk ($\alpha$) | Skew | Skew Std. Error | Kurtosis | Kurtosis Std. Error |
|---|---|---|---|---|---|
| Real-world | <0.001 | -1.151 | 0.129 | -0.027 | 0.256 |
| Simulated | <0.001 | -1.541 | 0.129 | 0.784 | 0.256 |

By further analysing histograms and boxplots, significant outliers were observed. The assumption for homogeneity of variance was preserved, as assessed using Levene's test. The distributions of averaged traffic flow were similar, as assessed visually. A Mann Whitney U test [113] was conducted and results showed the statistically significant difference between the two categories with traffic flow higher in *Real-World* (*Median (Mdn) = 70*) than *Simulated* (*Mdn = 68*), $U = 57{,}128.50, z = -2.75$ and $p = 0.006$. By analysing the "*effect size*" of

$\eta^2 = 0.23\%$, it could be state although there is a statistical difference between the groups, the measure of it was very small. Hence, to test the effects of reduced closures counts on improving congestion and travel delays using CAV-F the study will use the PTV Vissim simulation model with adjusted traffic flow by the percentage difference of 0.52%.

## 3.4. Simulation Setup

To test the hypothesis of reducing road congestion, improving travel time, and improving traffic throughput via the Dartford Crossing tunnel the study has identified three measuring parameters:

- *Queue Length Analysis* to verify the reduction in congestion.
- *Travel Time Analysis* to verify improvements in journey times.
- *Traffic Throughput Analysis* to verify the increase in hourly throughput.

Further the *Queue Length Analysis* and *Travel Time Analysis* are conducted in two phases. The *Phase I* will measure the impact of existing closures procedures for conventional DGVs and ALVs. The simulations will be conducted to measure the traffic queues and travel time for with varying degree of tunnel closure counts with AAHT obtained from Dartford Crossing data. In this phase, the results are compared for seven closure scenarios: *Six-Closures*, *Five-Closures*, *Four-Closures*, *Three-Closures*, *Two-Closures*, *One-Closure* and *Zero-Closure*. The closures are performed in simulation model based on configured probabilities for *Release*, *Extraction* and *Missed-Detect* closure categories.

*Phase II* will measure the improvement impact of CAV-F on existing system, the experiments will be conducted using CAV-F implementations of *Self-Declared*, *Undeclared* and *Missed-Detect* vehicles. The CAV-F implementations are based on the European project 'CoEXist' and PTV Vissim pre-defined driving behaviour parameters; acceleration and deceleration functions; and speed and time distributions for autonomous vehicles [80, 114].

The scope of the study is focused on the comparison of conventional vehicles with CAV-F, and not with determining the performance improvements of autonomous driving in general. The study will be using the recommended and pre-defined settings included in PTV Vissim based on CoEXist project, detailed in AV base setting manual [114]. For simulating and testing the impact of CAV-F on Dartford Crossing tunnel, it is assumed that secure and robust V2I communications between the *(AV) Self-Declared*, *(AV) Undeclared* and *(AV) Missed-Detect* vehicles and Dartford Crossing tunnel are in place. Thus, assuming a valid V2I message exchanges replacing check and allow procedures, no *Release*, *Extraction* or *Missed-Detect* closures will be simulated, and *AV-Self-Declared* vehicles will not travel to KMA but pass via two bores. The results from Phase II will be compared against the results from P*hase I* to determine the difference in queue lengths and travel time measurements. The results will be tallied against *Four-Closures* scenario as it has the highest AAH frequency for the analysed year. The experimental parameters for PTV Vissim simulations are set as follows:

- Vehicle count on A282 = 5000 vehicles/hr
- Vehicle count on A206 Eastbound = 750 vehicles/hr
- Vehicle count on A206 Westbound = 500 vehicles/hr
- Self-Declared closure duration = 77 seconds
- Undeclared closure duration = 187 seconds
- Missed-Detect closure duration = 141 seconds

These parameter setting are identical for both *Phase I* and *Phase II* experiments, except for closure logic, which are omitted in *Phase II*. The modified parameters are the closure counts for three closure scenarios. The results are evaluated for every five-minute interval of a 4500 seconds simulation run.

### **3.4.1.** Queue Length Analysis

The Vissim's *Queue Counter* object is used to estimate queue length from its location to the origin of the vehicles in simulation. For the study, the queue conditions are defined as:

$$Qbegin = v < 4.47 \text{ m/s} \tag{3}$$

$$Qend = v \geq 4.47 \text{ m/s} \tag{4}$$

Additionally, the vehicles on adjacent lanes are also considered. Four queue counters are positioned at one-meter distance before the four traffic signal heads on A282 West and East bores. The value of one meter is chosen to incorporate the Vissim's default standstill distance of 0.5 meters for traffic signal heads. Fifth queue counter is positioned at the N06 junction merger into A282 West bore. Each simulation run is randomised, representing a different hour where each hour simulates different traffic conditions. The Average Maximum Queue Length (AMQL) is observed for each minute interval over ten simulation runs to identify realistic queue patterns for seven different closure scenarios.

### 3.4.2. Travel Time Analysis

The Vissim's '*Vehicle Travel Time Measurements'* object is used to measure the mean travel time for a vehicle from a start point to destination point including wait time and/or holding time in parking areas. In total four measurement locations are positioned. Two are placed on A282 West and East bores, alongside two *'Data Collection Points*' at locations M25/4052L and M25/4052B. These will be providing travel information for all categories except for *Self-Declared* vehicles on respective bores. The remaining two are positioned at the end of FHB Lane1 & Lane2 and FHB Lane3 to obtain the travel time information for escorted *Self-Declared* vehicles via KMA. The Average Vehicle Travel Time (AVTT) aggregated over each minute interval over ten simulation runs will be used to identify the patterns for seven different closure scenarios on per hour basis.

### 3.4.3. Traffic Flow Analysis

The research hypothesises that by replacing all the 17.64% of conventional HGVs vehicles with CAV-F vehicles and simulating them alongside conventional *Cars* and *Buses* vehicle categories, the A282 four-lane road section of the Dartford Crossing tunnel would be able to accommodate 7,000 or more vehicles/hour without causing significant queue formations and significant reductions in journey times. The statement is based on the case study conducted on Dartford Crossing tunnel in 2009 [104] which highlighted that, the four-lane A282 road section should be able to support at least 7,000 vehicles/hour but was saturated at ~4,000 vehicles/hour with toll booths and currently is saturating at ~5,000 vehicles/hour, following the removal of toll booths in 2016 as observed by analysing the obtained Dartford Crossing tunnel data.

Thus, assuming that the Dartford Crossing tunnel infrastructure is fully equipped with C-ITS, V2V and V2I technologies and all relevant communication are established to ensure safe and verified passage of CAV-F vehicles without a need of *Extractions* or *Releases*, four determinants are identified which could help improve the traffic flow at the tunnel to achieve the target of >7,000 vehicles/hour flow. They are:

- *Headway* – smaller headway between CAV-F would provide more longitudinal space.
- *Standstill Distance* – reducing distance at traffic signals or in queues would allow more vehicles to enter the road network.

- *Scope of Connectivity* – a freight vehicle able to communicate with more vehicles and infrastructure objects would be more spatially aware and be able to make informed driving decisions.
- *Traffic Speed Limit* – increasing the overall speed limit would allow more vehicles to flow through Dartford Crossing quickly.

The first three determinants are categorised as *Driving Behaviour Changes* and are modified using PTV Vissim's driving parameters [79]. They are only applicable to a *CAV-F* vehicle category when the preceding vehicle is also a *CAV-F*. Table 7 defines four different driving behaviours used in the simulations.

**Table 7** CAV-F Driving Behaviours for Traffic Flow Analysis Simulations

| **Parameters** | **Autonomous Driving Behaviour** | | | |
|---|---|---|---|---|
| | **Normal** | **Mod 1** | **Mod 2** | **Aggressive** |
| Standstill Distance (CC0) | 1.50 m | 1.50 m | 1.00m | 1.00 m |
| Headway Time (CC1) | 0.9 s | 0.5 s | 0.5 s | 0.6 m |
| 'Following' Variation (CC2) | 0.00 m | 0.00 m | 0.00 m | 0.00 m |
| Threshold for Entering 'Following' (CC3) | -8.00 m | -8.00 m | -6.00 m | -6.00 m |
| Negative 'Following' Threshold (CC4) | -0.10 | -0.10 | -0.10 | -0.10 |
| Positive 'Following' Threshold (CC5) | 0.10 | 0.10 | 0.10 | 0.10 |
| Speed dependency of Oscillation (CC6) | 0.00 | 0.00 | 0.00 | 0.00 |
| Oscillation Acceleration (CC7) | 0.10 $m/s^2$ | 0.10 $m/s^2$ | 0.10 $m/s^2$ | 0.10 $m/s^2$ |
| Standstill Acceleration (CC8) | 3.50 $m/s^2$ | 3.50 $m/s^2$ | 3.50 $m/s^2$ | 4.00 $m/s^2$ |
| Acceleration with 80 km/h (CC9) | 1.50 $m/s^2$ | 1.50 $m/s^2$ | 1.50 $m/s^2$ | 2.00 $m/s^2$ |
| Max look ahead distance | 250.00 m | 250.00 m | 300.00 m | 300.00 m |
| No. of interaction objects | 2 | 4 | 4 | 10 |
| No. of interaction vehicles | 1 | 6 | 6 | 8 |
| Cooperative lane change | Enable | Enable | Enable | Enable |
| Time between direction changes | 0 s | 0 s | 0 s | 0 s |

The parameters labelled from *CC0* to *CC9* are related to the Wiedemann 99 model. The *Normal* and *Aggressive* driving behaviours are default and unmodified *CoEXist* behaviours, pre-defined in PTV Vissim. The *Mod-1* and *Mod-2* are modified from *Normal* for determinants *Headway*, *Standstill Distance* and *Scope of Connectivity* (*Number of interactions objects/vehicles*).

The determinant *Traffic Speed Limit* is identified because it is hypothesised that by increasing the current speed limit of 80 km/h (50 mph) on A282 road section, would allow the vehicles to enter and exit the Dartford Crossing tunnel quickly, in turn increasing the overall flow, under normal traffic conditions. To test the validity of this argument the simulations are modelled with three different speed limits: 80 km/h (50 mph), 88 km/h (55 mph) and 96 km/h (60 mph). A previous study [115] highlights the improved driving performances of CAV vehicles at higher speeds and in this study the increased speed limits are only applied to four AV driving behaviours.

The hourly simulation results are analysed based on the average of ten simulation runs, randomised using PTV Vissim's random seed generator which creates unique vehicle simulation initial conditions. This ensures no two simulations are similar as observed in the real-world. The results are then compared and discussed for Average Maximum Queue Length (AMQL) and Average Travel Time Measurements (ATTM) to support the hypothesis of increased traffic input.

## 3.5. Results

### 3.5.1. Phase I – Conventional Vehicles

The results will be detailed for mentioned queue and travel time measures of conventional vehicle driving behaviors.

#### 3.5.1.1. Queue Length Analysis

Figure 13 shows the AMQL on A282 and N06 road sections for *Release*, *Extraction* and *Miss-Detect* closure categories for given closure scenarios. The Shapiro-Wilk's test was performed to analyse the normality. The $p > 0.05$ was observed for *Four-Closures* scenario implying that the queue length was normal for only this scenario. The assumption of homogeneity was violated with $p < 0.001$ using Levene's test and the distribution of AMQL scores were not similar for all scenarios, as assessed by visual inspection of boxplots.

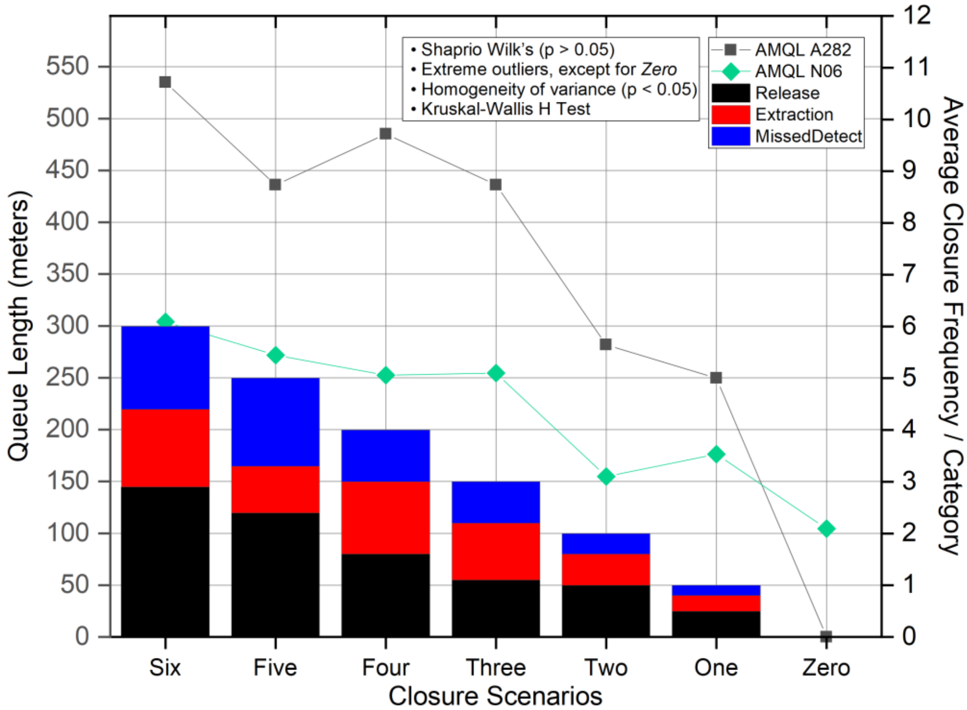


*Figure 13 Phase I Results - AMQL plot against varying scenarios*

A Kruskal-Wallis One-Way ANOVA [116] test showed that using non-parametric tests due to small and unequal sample size, even when assumption for equal variances was satisfied. For *Self-Declared* vehicle category, between-groups ANOVA test was used to examining the mean statistical differences of AVTT between the independent scenarios. A Kruskal-Wallis tests were conducted for mentioned five AMQL scores were statistically significantly different between the different levels of closure scenarios, *Pearson's chi-squared* $\chi^2(6) = 170.034,\ p < 0.001$. Subsequently, pairwise comparisons were performed using Dunn's procedure with a Bonferroni correction for multiple comparisons [117]. Adjusted p-values are presented. Table 8 shows the post-hoc test results between the scenarios.

**Table 8** A282 post-hoc pairwise comparisons between the scenarios

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **0-Closure-1-Closure** | -110.708 | 0.000* |
| **0-Closure-2-Closures** | -123.800 | 0.000* |
| **0-Closure-3-Closures** | -197.158 | 0.000* |
| **0-Closure-4-Closures** | -206.617 | 0.000* |
| **0-Closure-5-Closures** | -195.800 | 0.000* |
| **0-Closure-6-Closures** | -243.917 | 0.000* |
| **1-Closure-2-Closures** | -13.092 | 1.000 |
| **1-Closure-3-Closures** | -86.450 | 0.002* |
| **1-Closure-4-Closures** | -95.908 | 0.000* |
| **1-Closure-5-Closures** | -85.092 | 0.002* |
| **1-Closure-6-Closures** | -133.208 | 0.000* |
| **2-Closures-3-Closures** | -73.358 | 0.017* |
| **2-Closures-4-Closures** | -82.817 | 0.003* |

| | | |
|---|---|---|
| **2-Closures-5-Closures** | -72.000 | 0.022* |
| **2-Closures-6-Closures** | -120.117 | 0.000* |
| **3-Closures-4-Closures** | -9.458 | 1.000 |
| **3-Closures-6-Closures** | -46.758 | 0.696 |
| **4-Closures-6-Closures** | -37.300 | 1.000 |
| **5-Closures-3-Closures** | 1.358 | 1.000 |
| **5-Closures-4-Closures** | 10.817 | 1.000 |
| **5-Closures-6-Closures** | -48.117 | 0.596 |

Similar statistical analysis was conducted for N06 Slip Road section using the Kruskal-Wallis One-Way ANOVA test. The AMQL scores were statistically significantly different between the different levels of closure scenarios, $\chi^2(6) = 183.143, p < 0.001$. The pairwise comparisons were performed using Dunn's procedure with a Bonferroni correction as shown in Table 9.

**Table 9** N06 post-hoc N06 pairwise comparison of the scenarios

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **0-Closure-2-Closures** | -66.417 | 0.057 |
| **0-Closure-1-Closure** | -89.767 | 0.001* |
| **0-Closure-4-Closures** | -177.158 | 0.000* |
| **0-Closure-3-Closures** | -183.425 | 0.000* |
| **0-Closure-5-Closures** | -204.492 | 0.000* |
| **0-Closure-6-Closures** | -240.308 | 0.000* |
| **1-Closure-4-Closures** | -87.392 | 0.002* |
| **1-Closure-3-Closures** | -93.658 | 0.000* |
| **1-Closure-5-Closures** | -114.725 | 0.000* |
| **1-Closure-6-Closures** | -150.542 | 0.000* |
| **2-Closures-1-Closure** | 23.350 | 1.000 |
| **2-Closures-4-Closures** | -110.742 | 0.000* |
| **2-Closures-3-Closures** | -117.008 | 0.000* |
| **2-Closures-5-Closures** | -138.075 | 0.000* |
| **2-Closures-6-Closures** | -173.892 | 0.000* |
| **3-Closures-5-Closures** | -21.067 | 1.000 |
| **3-Closures-6-Closures** | -56.883 | 0.216 |
| **4-Closures-3-Closures** | 6.267 | 1.000 |
| **4-Closures-5-Closures** | -27.333 | 1.000 |
| **4-Closures-6-Closures** | -63.150 | 0.092 |
| **5-Closures-6-Closures** | -35.817 | 1.000 |

Analysing the results for the conventional vehicles queue measurements, it was observed that for both A282 and N06 road sections, the queue length tends to fall with the closure count, as anticipated. It was observed that the *Two-Closures* scenario seems to be a tipping point, where the AMQL starts to fall drastically with a ~35% decrease in length from *3-Closure* and ~42% from the most frequent *Four-Closures* scenario on the A282 road section, and ~39% decrease for both the scenarios for N06 road section. From the simulations it was also observed that following an independent closure event, it took approximately 15-25 minutes for the queues to dissipate on the full length of simulated A282 road section.

Another interesting point noted was that for A282 road section the queues disappeared completely with zero closure scenario but not for N06 road section. This seemed to be the case because of DGVs and ALVs traffic joins N06 from KMA, along with traffic from nearby A206 roads. From the Dartford Crossing data, it was observed that ~89% of vehicles re-join the traffic from KMA, suggesting that the *Self-Declared* category of vehicles would surely benefit from CAV-F implementations, by utilising V2I messages for verifying a vehicle to travel through A282 without a trip to KMA.

#### 3.5.1.2. Vehicle Travel Time Analysis

Figure 14 shows the AVTT of six vehicles categories on per minute basis for each of the seven closure scenarios.

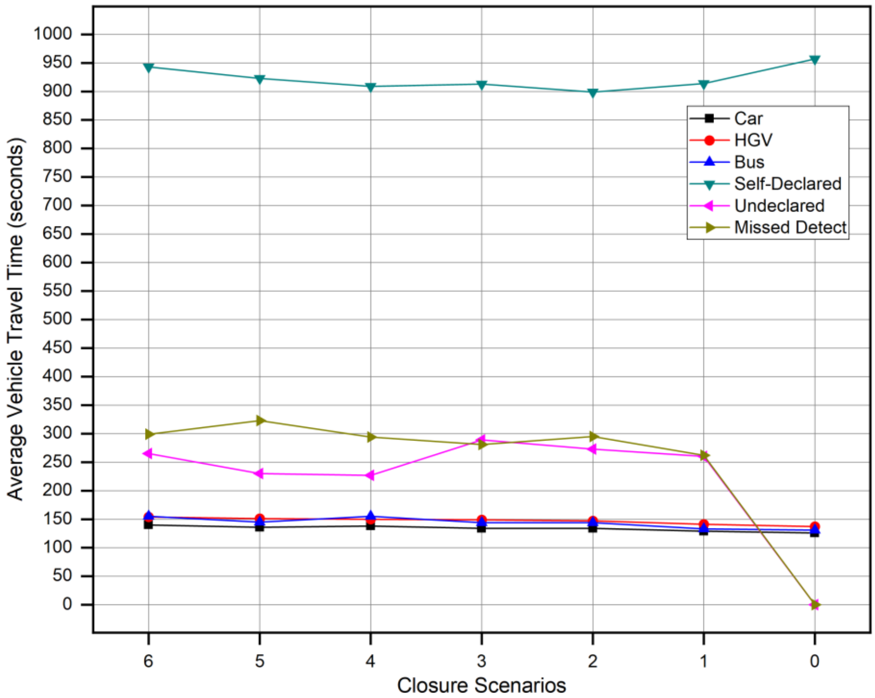


*Figure 14 Phase I Results - AVTT per vehicle categories against various scenarios.*

The Kruskal-Wallis One-Way ANOVA test was identified for all vehicle categories except for *Self-Declared* vehicles which used One-Way ANOVA, to examine statistical differences in the distribution of AVTT.

For *Cars* vehicle category the AVTT scores were statistically significantly different between the closure scenarios ($\chi^2(6) = 131.911, p < 0.001, N = 518$). The post hoc analysis are presented in Table 10.

**Table 10** *Cars* vehicle category post-hoc pairwise comparison between the scenarios

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **0-Closures-1-Closure** | -60.689 | 0.280 |
| **0-Closures-2-Closures** | -121.764 | 0.000* |
| **0-Closures-3-Closures** | -158.696 | 0.000* |
| **0-Closures-4-Closures** | -196.345 | 0.000* |
| **0-Closures-5-Closures** | -196.365 | 0.000* |
| **0-Closures-6-Closures** | -222.493 | 0.000* |
| **1-Closure-2-Closures** | -61.074 | 0.268 |
| **1-Closure-3-Closures** | -98.007 | 0.001* |
| **1-Closure-4-Closures** | -135.655 | 0.000* |
| **1-Closure-5-Closures** | -135.676 | 0.000* |
| **1-Closure-6-Closures** | -161.804 | 0.000* |
| **2-Closures-3-Closures** | -36.932 | 1.000 |
| **2-Closures-4-Closures** | -74.581 | 0.049* |
| **2-Closures-5-Closures** | -74.601 | 0.049* |
| **2-Closures-6-Closures** | -100.730 | 0.001* |
| **3-Closures-4-Closures** | -37.649 | 1.000 |
| **3-Closures-5-Closures** | -37.669 | 1.000 |
| **3-Closures-6-Closures** | -63.797 | 0.195 |
| **4-Closures-5-Closures** | -0.020 | 1.000 |
| **4-Closures-6-Closures** | -26.149 | 1.000 |
| **5-Closures-6-Closures** | -26.128 | 1.000 |

For *HGVs* vehicle category the AVTT scores were statistically significantly different between the closure scenarios ($\chi^2(6) = 105.261, p < 0.001, N = 512$). The post hoc analysis are presented in Table 11.

**Table 11** *HGV* vehicle category post-hoc pairwise comparison between the scenarios.

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **0-Closures-1-Closure** | -53.973 | 0.576 |
| **0-Closures-2-Closures** | -119.144 | 0.000* |
| **0-Closures-3-Closures** | -151.605 | 0.000* |
| **0-Closures-4-Closures** | -167.432 | 0.000* |
| **0-Closures-5-Closures** | -178.699 | 0.000* |
| **0-Closures-6-Closures** | -198.596 | 0.000* |
| **1-Closure-2-Closures** | -65.171 | 0.163 |
| **1-Closure-3-Closures** | -97.632 | 0.001* |
| **1-Closure-4-Closures** | -113.459 | 0.000* |
| **1-Closure-5-Closures** | -124.726 | 0.000* |
| **1-Closure-6-Closures** | -144.623 | 0.000* |
| **2-Closures-3-Closures** | -32.461 | 1.000 |
| **2-Closures-4-Closures** | -48.288 | 1.000 |
| **2-Closures-5-Closures** | -59.555 | 0.314 |
| **2-Closures-6-Closures** | -79.452 | 0.025 |
| **3-Closures-4-Closures** | -15.827 | 1.000 |
| **3-Closures-5-Closures** | -27.094 | 1.000 |
| **3-Closures-6-Closures** | -46.991 | 1.000 |
| **4-Closures-5-Closures** | -11.267 | 1.000 |

| | | |
|---|---|---|
| **4-Closures-6-Closures** | -31.164 | 1.000 |
| **5-Closures-6-Closures** | -19.897 | 1.000 |

For *Buses* vehicle category the AVTT scores were statistically significantly different between the closure scenarios ($\chi^2(6) = 17.321, p = 0.008, N = 492$). The post hoc analysis are presented in **Error! Reference source not found.**.

**Table 12** *Buses* vehicle category post-hoc pairwise comparison between the scenarios

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **1-Closure-0-Closures** | 4.739 | 1.000 |
| **1-Closure-3-Closures** | -15.758 | 1.000 |
| **1-Closure-2-Closures** | -33.190 | 1.000 |
| **1-Closure-5-Closures** | -59.710 | 0.245 |
| **1-Closure-6-Closures** | -60.707 | 0.269 |
| **1-Closure-4-Closures** | -69.394 | 0.078 |
| **0-Closures-3-Closures** | -11.019 | 1.000 |
| **0-Closures-2-Closures** | -28.451 | 1.000 |
| **0-Closures-5-Closures** | -54.971 | 0.426 |
| **0-Closures-6-Closures** | -55.967 | 0.457 |
| **0-Closures-4-Closures** | -64.654 | 0.145 |
| **3-Closures-2-Closures** | 17.432 | 1.000 |
| **3-Closures-5-Closures** | -43.952 | 1.000 |
| **3-Closures-6-Closures** | -44.948 | 1.000 |
| **3-Closures-4-Closures** | -53.636 | 0.504 |
| **2-Closures-5-Closures** | -26.520 | 1.000 |
| **2-Closures-6-Closures** | -27.516 | 1.000 |
| **2-Closures-4-Closures** | -36.203 | 1.000 |
| **5-Closures-6-Closures** | -0.996 | 1.000 |
| **5-Closures-4-Closures** | 9.683 | 1.000 |
| **6-Closures-4-Closures** | 8.687 | 1.000 |

Analysing *Undeclared* and *Missed-Detect* categories using Kruskal-Wallis test showed that the distributions were not approximately similar for all the scenarios, as assessed by visual inspection of a boxplot. AVTT was approximately statistically similar between the scenarios for *Undeclared* category, $\chi^2(5) = 1.926, p = 0.859, N = 63$. For *Missed- Detect* category, AVTT score was statistically significantly different between the scenarios, $\chi^2(5) = 13.680, p = 0.018, N = 56$. The pairwise comparisons were performed using Dunn's procedure with a Bonferroni correction for multiple scenarios of *Missed-Detect* category. This post hoc analysis revealed AVTT for both the vehicle categories were approximately statistically similar for all scenario combinations, except for *Zero-Closure* scenario for which simulated no *Undeclared* or *Missed-Detect* vehicles.

A One-Way ANOVA was conducted for *Self-Declared* vehicle category showed that the AVTT between the scenarios was approximately statistically similar, $F(6,474) = 0.293, p = 0.940$

and with the small effect size of $\eta^2 = 0.004$ between the closure scenarios. By this it was determine that the reduction in number of closures, and even with zero closures, there is no significant impact on the travel time for *Self-Declared* vehicles as they must stop at KMA for inspection, even if no vehicle is required to be *Released*.

Analysing the vehicle travel time results for *Phase I*, it was revealed that, AVTT for *Car*, *HGVs* and *Bus* vehicle categories was considerably low at ∼2.5 minutes with an observed maximum delay of approximately a minute, during a free-flow period. For *Car* and *HGVs*, *One-Closure* scenario was the tipping point, where AVTT score improved by ∼6% from higher closure scenarios. Alternatively, during a closure event, the Average Maximum Travel Time (AMTT) for three categories was increased by ∼71% from AVTT for all the scenarios except for *Zero-Closure* scenario, which saw an increase of ∼21%. This significant increase could be because of multiple scenarios occurring together or close to each other, which does reflect real-world closure patterns. The analysis of *Missed-Detect* and *Undeclared* categories revealed the AVTT of ∼4 minutes and AMTT of ∼6 minutes, for both the categories, which is ∼60% higher than previous three categories. But AVTT and AMTT were approximately similar for all closure scenarios. This could be because of the additional closure duration for these vehicles at ∼2 minutes. The biggest impact on the travel time was observed for the *Self-Declared* vehicle category with AVTT of ∼15 minutes and AMTT of ∼40 minutes. Also, the AVTT and AMTT were similar between all the scenarios, even for *Zero-Closure* scenario without any *Release* or *Extraction* closure events. This is because *DGVs* and *ALVs* vehicles must always stop at KMA for inspection. The average delay for this category was observed at ∼10 minutes for vehicles which were resent to A282 via N06 and ∼3 minutes for *Released* vehicles, which means if the vehicles are not *Released*, then they have an added delay of duration spent in KMA for inspection, which could be between ∼15 minutes to ∼10 hours, as observed from the Dartford Crossing data. Furthermore, the travel time for *Released* vehicles would be greater than what is reported from simulation results, as true travel time is not possible to be determined using the model, as *Release* closure procedure does not match the real-world, where up to nine vehicles are queues for an unknown duration before they are released.

### 3.5.2. Phase II – CAV-F Vehicles

This section compares the results from autonomous vehicles driving behaviour with conventional vehicles driving.

### 3.5.2.1. Queue Length Analysis Results

Figure 15 shows the AMQL for *Release*, *Extraction* and *Missed-Detect* closure categories over five closure scenarios: *Four-Closures*, *Zero-Closure*, *AV-Cautious*, *AV-Normal* and *AV-Aggressive*.

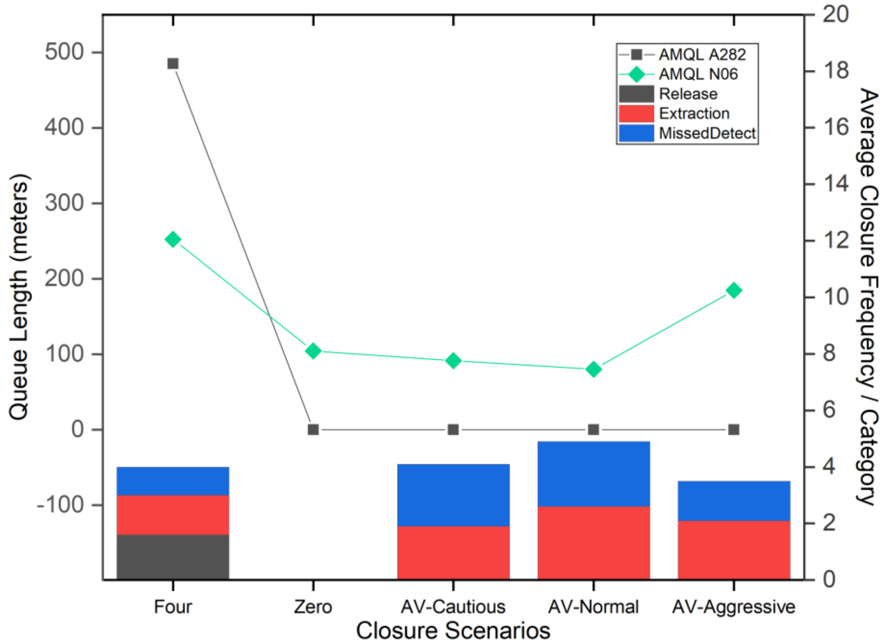


*Figure 15 Phase II Results – AMQL plots for varying scenarios*

No queues are formed on A282 for *AV-Cautious*, *AV-Normal* and *AV-Aggressive* scenarios with autonomous implementations of *Self-Declared*, *Undeclared* and *Missed-Detect* vehicle categories. The queue behaviour was significantly different for *4-Closure* scenario with all other closure scenarios. It could be noted that the *Zero-Closure* scenario is very unlikely with existing procedures at Dartford Crossing unless replaced by CAV-F implementations.

Observing N06 Slip road section, it is interesting to note that even for all closure scenarios, unlike the results for A282 road section, queues are observed on the slip road. By statistically analysing the AMQL for N06, using the Shapiro-Wilk's test, it was observed that the distribution for all the scenarios, except for *Zero-Closure* ($p = 0.053$) and *AV-Aggressive* ($p = 0.755$), was not normally distributed, $p < 0.05$. Further it was observed that distribution for most of the scenarios was positively skewed and with significant outliers, as observed using boxplots. The data was log transformed ($\log_{10}$) for all closure categories. Re-running the Shapiro-Wilk's test on transformed data showed that the distributions were approximately statistically normally for most of the scenarios. Using the Levene's test, assumption of homogeneity between the groups was violated, but as ANOVA is considered robust for approximately normally distributed data with fewer outliers and similar sample size [109, 118, 119], the between-groups ANOVA with Games-Howell post hoc mean test was used to determine if the AMQL score between the groups is statistically different.

A one-way Welch ANOVA was conducted, and the results showed that AMQL score was statistically significantly different between different closure scenarios, $Welch\ F(4, 145.082) = 101.458, p < 0.001$. The AMQL score increased from the *AV-Normal* scenario (*M = 74.81, SD = 1.44*) to the *AV-Cautious* (*M = 83.84, SD = 1.52*), *Zero-Closure* (*M = 99.93, SD = 1.36*), *AV-Aggressive* (*M = 179.85, SD = 1.28*), and *Four-Closures* (*M = 224.28, SD = 1.71*) scenario, in that order. Games-Howell post hoc analysis is presented in table 13.

**Table 13** Games-Howell post-hoc analysis between the scenarios

| **Dependent Variable: N06 Slip Road (Log10)** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **0-Closures** | AV-Cautious | 0.07627 | 0.072 | -0.0042 | 0.1567 |
| | AV-Normal | .12576* | 0.000 | 0.0519 | 0.1997 |
| | AV-Aggressive | -.25519* | 0.000 | -0.3163 | -0.1941 |
| | 4-Closures | -.35107* | 0.000 | -0.4472 | -0.2550 |
| **AV-Cautious** | 0-Closures | -0.07627 | 0.072 | -0.1567 | 0.0042 |
| | AV-Normal | 0.04949 | 0.501 | -0.0363 | 0.1352 |
| | AV- Aggressive | -.33146* | 0.000 | -0.4067 | -0.2562 |
| | 4-Closures | -.42734* | 0.000 | -0.5326 | -0.3221 |
| **AV-Normal** | 0-Closures | -.12576* | 0.000 | -0.1997 | -0.0519 |
| | AV-Cautious | -0.04949 | 0.501 | -0.1352 | 0.0363 |
| | AV- Aggressive | -.38094* | 0.000 | -0.4491 | -0.3128 |
| | 4-Closures | -.47683* | 0.000 | -0.5773 | -0.3764 |
| **AV-Aggressive** | 0-Closures | .25519* | 0.000 | 0.1941 | 0.3163 |
| | AV-Cautious | .33146* | 0.000 | 0.2562 | 0.4067 |
| | AV-Normal | .38094* | 0.000 | 0.3128 | 0.4491 |
| | 4-Closures | -.09588* | 0.036 | -0.1877 | -0.0040 |
| **4-Closures** | 0-Closures | .35107* | 0.000 | 0.2550 | 0.4472 |

| | | | | | |
|---|---|---|---|---|---|
| | AV-Cautious | .42734* | 0.000 | 0.3221 | 0.5326 |
| | AV-Normal | .47683* | 0.000 | 0.3764 | 0.5773 |
| | AV- Aggressive | .09588* | 0.036 | 0.0040 | 0.1877 |

The *Phase II* showed significant improvements in reduction of queues, limited only to *AV-Cautious* and *AV-Normal* driving behaviour. In contrast, the *AV-Aggressing* driving method performed significantly worse than the two AV categories, both for AMQL measurements. Although, for A282 road section, zero queues were formed all *AV* scenarios, but queues were formed N06 road section for all scenarios in either phases. Comparing the queues on N06, showed that with *AV-Cautious* and *AV-Normal* scenarios the queue lengths improved by ∼12% and ∼23%, respectively from *Zero-Closure* scenario and an improvement of ∼59% from conventional closure scenarios. For *AV-Aggressive* scenario the queue length was ∼131% higher than *AV-Normal* scenario and only ∼27% lower than *4-Closure* scenarios. In other words, it could be inferred that for *AV-Aggressive* scenarios, queues of length greater than ∼185 meters were more frequent, even with zero queues on A282. The reason for this could be disproportionately low traffic count of CAV-F vehicles in comparison to surrounding conventional vehicles for *AV-Aggressive* and sensitive driving parameters setup for near perfect simulation of fully autonomous vehicles.

#### **3.5.2.2.** Travel Time Analysis Results

Figure 16 shows the AVTT on per minute basis for each of the five closure scenarios: *Four-Closures*, *Zero-Closure*, *AV-Cautious*, *AV-Normal* and *AV-Aggressive*.

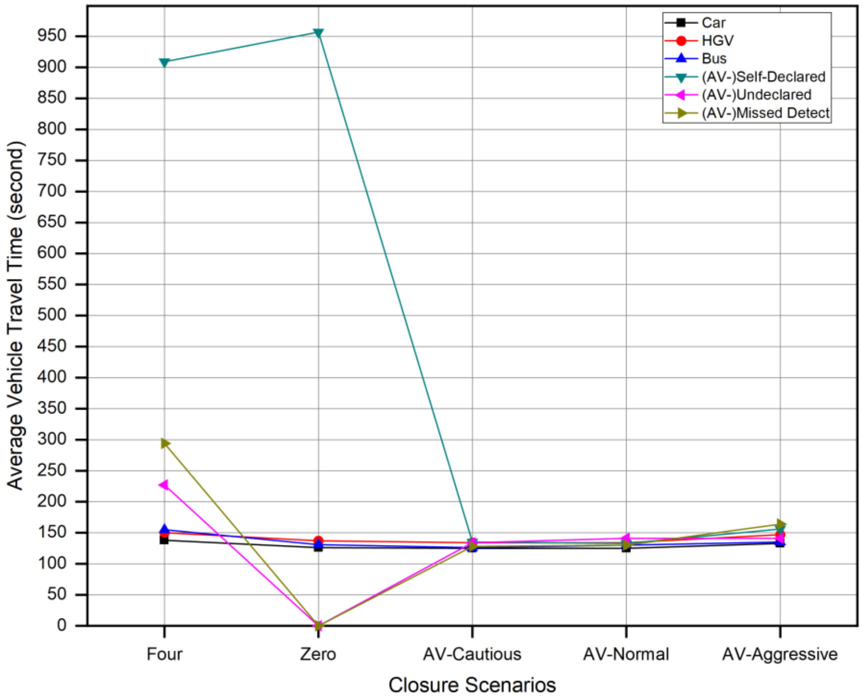


*Figure 16 Phase II Results – AVTT per vehicle categories for varying scenarios*

By statistically analysing the AVTT for different closure scenarios per category, using the Shapiro-Wilk's test, it was observed the for all the vehicle categories, except for *(AV) Self-Declared* vehicle category ($p > 0.05$), the distribution was not normally distributed, $p < 0.05$. Using the Levene's test, assumption of homogeneity was violated for all vehicle categories, $p < 0.001$. The Kruskal-Wallis One-Way ANOVA test was identified to examine statistical differences in the distribution of AVTT between independent scenarios. A Kruskal-Wallis test was conducted. Median AVTT scores were approximately statistically similar between the all the closure scenarios for all four vehicle categories, *Car* ($\chi^2(4) = 213.163, p < 0.001, N = 370$); *HGVs* ($\chi^2(4) = 206.139, p < 0.001, N = 366$), *Bus* ($\chi^2(4) = 57.249, p < 0.001, N = 357$) and *(AV) Missed-Detect* ($\chi^2(3) = 28.921, p < 0.001, N = 65$). The pairwise comparisons were performed using Dunn's procedure.

For *Cars*, the post hoc analysis is presented in Table 14.

**Table 14** *Cars* vehicle category pairwise comparison between the scenarios.

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **AV-Normal-AV-Cautious** | 18.176 | 1.000 |
| **AV-Normal-0-Closures** | 56.345 | 0.012* |
| **AV-Normal-4-Closures** | -177.088 | 0.000* |
| **AV-Normal-AV-Aggressive** | -190.655 | 0.000* |
| **AV-Cautious-0-Closures** | 38.169 | 0.278 |
| **AV-Cautious-4-Closures** | -158.912 | 0.000* |
| **AV-Cautious-AV-Aggressive** | -172.480 | 0.000* |
| **0-Closures-4-Closures** | -120.743 | 0.000* |

| | | |
|---|---|---|
| **0-Closures-AV-Aggressive** | -134.311 | 0.000* |
| **4-Closures-AV-Aggressive** | 13.568 | 1.000 |

For *HGVs*, the post hoc analysis is presented in Table 15.

**Table 15** *HGVs* vehicle category pairwise comparisons between the scenarios

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **AV-Normal-AV-Cautious** | 2.007 | 1.000 |
| **AV-Normal-0-Closures** | 63.767 | 0.003* |
| **AV-Normal-4-Closures** | -168.240 | 0.000* |
| **AV-Normal-AV-Aggressive** | -184.371 | 0.000* |
| **AV-Cautious-0-Closures** | 61.760 | 0.004* |
| **AV-Cautious-4-Closures** | -166.233 | 0.000* |
| **AV-Cautious-AV-Aggressive** | -182.364 | 0.000* |
| **0-Closures-4-Closures** | -104.473 | 0.000* |
| **0-Closures-AV-Aggressive** | -120.604 | 0.000* |
| **4-Closures-AV-Aggressive** | 16.131 | 1.000 |

For *Buses,* the post hoc analysis is presented in Table 16.

**Table 16** *Buses* vehicle category pairwise comparison between the scenarios.

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **AV-Normal-AV-Cautious** | 1.565 | 1.000 |
| **AV-Normal-0-Closures** | 34.346 | 0.463 |
| **AV-Normal-4-Closures** | -84.295 | 0.000* |
| **AV-Normal-AV-Aggressive** | -98.978 | 0.000* |
| **AV-Cautious-0-Closures** | 32.782 | 0.581 |
| **AV-Cautious-4-Closures** | -82.731 | 0.000* |
| **AV-Cautious-AV-Aggressive** | -97.414 | 0.000* |
| **0-Closures-4-Closures** | -49.949 | 0.040* |
| **0-Closures-AV-Aggressive** | -64.632 | 0.002* |
| **4-Closures-AV-Aggressive** | 14.683 | 1.000 |

For *(AV) Missed-Detect*, the post hoc analysis is presented in Table 17.

**Table 17** *(AV) Missed-Detect* vehicle category pairwise comparison between the scenarios.

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **AV-Cautious-AV-Normal** | -5.812 | 1.000 |
| **AV-Cautious-AV-Aggressive** | -16.886 | 0.082 |
| **AV-Cautious-4-Closures** | -36.986 | 0.000* |
| **AV-Normal-AV-Aggressive** | -11.074 | 0.896 |
| **AV-Normal-4-Closures** | -31.174 | 0.000* |
| **AV-Aggressive-4-Closures** | -20.100 | 0.091 |

Analysing *(AV) Self-Declared* and *(AV) Undeclared* categories using a Kruskal-Wallis test showed that the distributions were not approximately similar for all the scenarios, as assessed by visual inspection of a boxplot. AVTT scores were statistically significantly different between the independent closure scenarios for *(AV) Self-Declared* category,

$\chi^2(4) = 277.596, p < 0.001, N = 357$ and *(AV) Undeclared* category, $\chi^2(3) = 32.501, p < 0.001, N = 69$. For *(AV) Self-Declared*, the post hoc analysis is presented in Table 18.

**Table 18** *(AV) Self-Declared* vehicle category pairwise comparison between the scenarios

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **AV-Normal-AV-Cautious** | 0.473 | 1.000 |
| **AV-Normal-AV-Aggressive** | -72.781 | 0.000* |
| **AV-Normal-4-Closures** | -199.976 | 0.000* |
| **AV-Normal-0-Closures** | 205.860 | 0.000* |
| **AV-Cautious-AV-Aggressive** | -72.308 | 0.000* |
| **AV-Cautious-4-Closures** | -199.503 | 0.000* |
| **AV-Cautious-0-Closures** | 205.387 | 0.000* |
| **AV-Aggressive-4-Closures** | -127.195 | 0.000* |
| **AV-Aggressive-0-Closures** | 133.079 | 0.000* |
| **4-Closures-0-Closures** | 5.884 | 1.000 |

For *(AV) Undeclared*, the post hoc analysis is presented in Table 19.

**Table 19** *(AV) Undeclared* vehicle category pairwise comparison between the scenarios

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **AV-Cautious-AV-Normal** | -9.794 | 1.000 |
| **AV-Cautious-AV-Aggressive** | -13.636 | 0.417 |
| **AV-Cautious-4-Closures** | -40.871 | 0.000* |
| **AV-Normal-AV-Aggressive** | -3.842 | 1.000 |
| **AV-Normal-4-Closures** | -31.077 | 0.000* |
| **AV-Aggressive-4-Closures** | -27.235 | 0.002* |

Comparing the results in *Phase II* for travel time measurements, it could be observed that *AV-Cautious* and *AV-Normal* scenarios performed significantly better. It was observed that AVTT for *Four-Closures* and *AV-Aggressive* scenarios were significantly different from remaining closure scenarios, for all vehicle categories. The AVTT for *Car*, *HGVs* and *Bus* categories improved by ~6%, for *Undeclared* and *Missed-Detect* by ~74% and for *Self-Declared* category by ~102% i.e. an improvement by ~8 minutes on average. Another statistic showed that, as there were no queues and traffic was free flowing with a mix of autonomous vehicles. The AMTT for *Cars*, *HGVs* and *Bus* improved by ~104%, ~59% and ~37%, respectively, i.e. an improvement of ~4 minutes for *Car* and *HGVs* categories and ~2 minutes for *Bus*. The biggest winner was the *Self-Declared* category for which AMTT improved by ~18 minutes, which was the average time spent in KMA and on N06 road section during *Phase I* simulations. Surprisingly, the AMTT for *Undeclared* and *Missed-Detect* vehicle category only improved by mere ~2minutes and ~30 seconds, respectively.

## 3.5.3. Traffic Flow Analysis Results

The results are discussed for AMQL and ATTM in two groups. The first group names as *Driving Behaviour Changes* will analyse performance between four driving behaviours mentioned in Table 7 for varying traffic flow ranging from 5,000 vehicles/hour to 10,000 vehicles/hour. In the second group, named as *Traffic Speed Limit*, the results will analyse the performance of varying speed limits: 80 km/hour, 88 km/hour, and 96 km/hour for four identified driving behaviours with a fixed 7,000 vehicles/hour simulated traffic flow. The results are compared firstly withing the groups to determine the changes with the increase in traffic flow, and secondly between the groups to determine which driving behaviour or speed profile yields promising results.

### 3.5.3.1. Driving Behaviour Changes – AMQL Analysis

Figure 17 shows the AMQL results for varying driving behaviours on A282 and N06 road sections of Dartford Crossing tunnel both for within and in between comparisons.

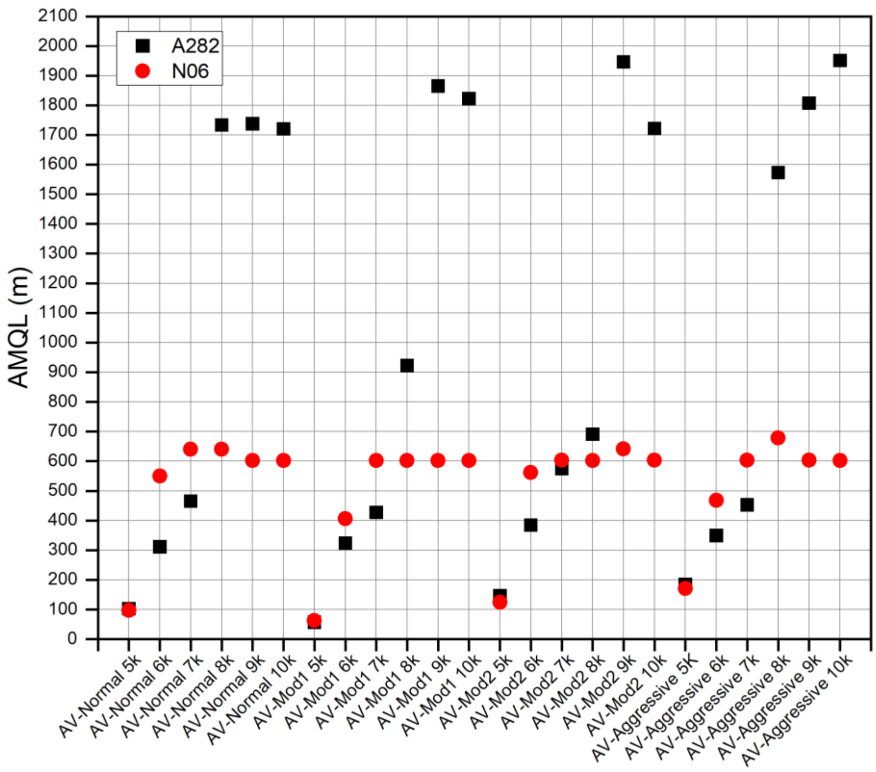


*Figure 17 AMQL plot for varying vehicle counts and driving behaviours*

By analysing the AMQL for within the groups and the One-Way ANOVA with Welch's test showed that the queues between the increasing traffic flows was statistically significantly different Welch's $F(5, 141.03) = 983.03$, $p < 0.005$. The Games-Howell post-hoc test within the group is presented in Table 20.

**Table 20** *AV-Normal* driving behaviour pairwise comparison within the group

| Dependent Variable: AV-Normal | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **5K** | 6K | -325.09* | 0.000 | -375.44 | -274.74 |
| | 7K | -512.46* | 0.000 | -540.04 | -484.88 |
| | 8K | -1004.55* | 0.000 | -1125.91 | -883.20 |
| | 9K | -1074.42* | 0.000 | -1206.70 | -942.14 |
| | 10K | -1049.88* | 0.000 | -1171.13 | -928.65 |
| **6K** | 5K | 325.09* | 0.000 | 274.74 | 375.44 |
| | 7K | -187.37* | 0.000 | -243.61 | -131.14 |
| | 8K | -679.46* | 0.000 | -809.55 | -549.38 |
| | 9K | -749.32* | 0.000 | -889.64 | -609.02 |
| | 10K | -724.79* | 0.000 | -854.77 | -594.82 |
| **7K** | 5K | 512.46* | 0.000 | 484.88 | 540.04 |
| | 6K | 187.37* | 0.000 | 131.14 | 243.61 |
| | 8K | -492.09* | 0.000 | -615.94 | -368.25 |
| | 9K | -561.95* | 0.000 | -696.52 | -427.40 |
| | 10K | -537.42* | 0.000 | -661.15 | -413.70 |
| **8K** | 5K | 1004.55* | 0.000 | 883.20 | 1125.91 |
| | 6K | 679.46* | 0.000 | 549.38 | 809.55 |
| | 7K | 492.09* | 0.000 | 368.25 | 615.94 |
| | 9K | -69.86 | 0.860 | -246.30 | 106.56 |
| | 10K | -45.33 | 0.971 | -213.89 | 123.23 |
| **9K** | 5K | 1074.42* | 0.000 | 942.14 | 1206.70 |
| | 6K | 749.32* | 0.000 | 609.02 | 889.64 |
| | 7K | 561.95* | 0.000 | 427.40 | 696.52 |
| | 8K | 69.86 | 0.860 | -106.56 | 246.30 |
| | 10K | 24.53 | 0.999 | -151.81 | 200.89 |
| **10K** | 5K | 1049.88* | 0.000 | 928.65 | 1171.13 |
| | 6K | 724.79* | 0.000 | 594.82 | 854.77 |
| | 7K | 537.42* | 0.000 | 413.70 | 661.15 |
| | 8K | 45.33 | 0.971 | -123.23 | 213.89 |
| | 9K | -24.53 | 0.999 | -200.89 | 151.81 |

For *AV-Mod1* and *AV-Mod2* driving behaviours, the Kruskal-Wallis test was conducted and it was observed to be statistically significantly different between all the flow for *AV-Mod1* and *AV-Mod2* driving behaviours, *AV-Mod1* $X^2$ *(5) = 330.28*, $p < 0.005$ and *AV-Mod2* $X^2$ *(5) = 327.98*, $p < 0.005$. Subsequently, pairwise comparisons were performed using Dunn's (1964) procedure. This post hoc analysis for *AV-Mod1* is presented in Table 21 and *AV-Mod2* is presented in Table 22.

**Table 21** *AV-Mod1* driving behaviour pairwise comparison within group

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **5K-6K** | -64.817 | 0.010* |
| **5K-7K** | -117.542 | 0.000* |
| **5K-8K** | -181.925 | 0.000* |
| **5K-9K** | -266.200 | 0.000* |
| **5K-10K** | -269.517 | 0.000* |
| **6K-7K** | -52.725 | 0.083* |
| **6K-8K** | -117.108 | 0.000* |
| **6K-9K** | -201.383 | 0.000* |
| **6K-10K** | -204.700 | 0.000* |
| **7K-8K** | -64.383 | 0.011* |
| **7K-9K** | -148.658 | 0.000* |
| **7K-10K** | -151.975 | 0.000* |
| **8K-9K** | -84.275 | 0.000* |
| **8K-10K** | -87.592 | 0.000* |
| **9K-10K** | -3.317 | 1.000 |

**Table 22** *AV-Mod2* driving behaviour pairwise comparison within group

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **5K-6K** | -64.000 | 0.011* |
| **5K-7K** | -132.433 | 0.000* |
| **5K-8K** | -163.950 | 0.000* |
| **5K-10K** | -262.933 | 0.000* |
| **5K-9K** | -276.683 | 0.000* |
| **6K-7K** | -68.433 | 0.005* |
| **6K-8K** | -99.950 | 0.000* |
| **6K-10K** | -198.933 | 0.000* |
| **6K-9K** | -212.683 | 0.000* |
| **7K-8K** | -31.517 | 1.000 |
| **7K-10K** | -130.500 | 0.000* |
| **7K-9K** | -144.250 | 0.000* |
| **8K-10K** | -98.983 | 0.000* |
| **8K-9K** | -112.733 | 0.000* |
| **10K-9K** | 13.750 | 1.000 |

By analysing *Aggressive* driving mode for AMQL using the One-Way ANOVA Welch's test showed that the AMQL between the varying *AV-Aggressive* traffic flows was statistically significantly different between the flows, Welch's $F(5, 150.60) = 785.19, p < 0.005$. The Games-Howell's post hoc test for within the group is presented in Table 23.

**Table 23** *AV-Aggressive* driving behaviour pairwise comparison within the group

| Dependent Variable: ***AV-Aggressive*** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **5K** | 6K | -187.58* | 0.000 | -224.28 | -150.89 |
| | 7K | -463.14* | 0.000 | -489.22 | -437.07 |
| | 8K | -894.93* | 0.000 | -1011.29 | -778.58 |
| | 9K | -1034.50* | 0.000 | -1155.74 | -913.28 |
| | 10K | -1007.26* | 0.000 | -1154.00 | -860.52 |
| **6K** | 5K | 187.58* | 0.000 | 150.89 | 224.28 |
| | 7K | -275.55* | 0.000 | -317.29 | -233.83 |
| | 8K | -707.34* | 0.000 | -827.78 | -586.91 |
| | 9K | -846.92* | 0.000 | -972.07 | -721.78 |
| | 10K | -819.67* | 0.000 | -969.66 | -669.70 |
| **7K** | 5K | 463.14* | 0.000 | 437.07 | 489.22 |
| | 6K | 275.56* | 0.000 | 233.83 | 317.29 |
| | 8K | -431.78* | 0.000 | -549.74 | -313.83 |
| | 9K | -571.36* | 0.000 | -694.13 | -448.60 |
| | 10K | -544.11* | 0.000 | -692.12 | -396.11 |
| **8K** | 5K | 894.93* | 0.000 | 778.58 | 1011.29 |
| | 6K | 707.34* | 0.000 | 586.91 | 827.78 |
| | 7K | 431.78* | 0.000 | 313.83 | 549.74 |
| | 9K | -139.57 | 0.146 | -304.18 | 25.03 |
| | 10K | -112.32 | 0.488 | -296.08 | 71.42 |
| **9K** | 5K | 1034.50* | 0.000 | 913.28 | 1155.74 |
| | 6K | 846.92* | 0.000 | 721.78 | 972.07 |
| | 7K | 571.36* | 0.000 | 448.60 | 694.13 |
| | 8K | 139.57 | 0.146 | -25.03 | 304.18 |
| | 10K | 27.24 | 0.998 | -159.48 | 213.98 |
| **10K** | 5K | 1007.26* | 0.000 | 860.52 | 1154.00 |
| | 6K | 819.67* | 0.000 | 669.70 | 969.66 |
| | 7K | 544.11* | 0.000 | 396.11 | 692.12 |
| | 8K | 112.32 | 0.488 | -71.42 | 296.08 |
| | 9K | -27.24 | 0.998 | -213.98 | 159.48 |

By analysing the AMQL for between the groups, the One-Way ANOVA with Welch's test showed that the AMQL between the *AV-Normal* (*N = 60, M =727.72, SD = 174.46*), *AV-Mod1* (*N = 60, M =676.82, SD = 106.23*), *AV-Mod2* (*N = 60, M =720.68, SD = 106.07*) and *AV-Aggressive* (*N = 60, M =705.06, SD = 174.69*) was statistically significantly similar, Welch's $F(3, 128.09) = 2.15$, $p = 0.097$, $\eta^2 = 0.018$.

The analysis showed that overall *AV-Mod2* version of autonomous vehicle driving behaviour performed better than the other driving behaviours. On the A282 road section, *AV-Mod2* was able to restrict the AMQL to ~700m with traffic flow up to 8,000 vehicles/hour and *Mod1* to ~900m. The vehicle count of 8,000 vehicles/ hour was observed to be the tipping point. It was also observed that, for all AV driving behaviours, the AMQL increased drastically by ~350% (i.e. from ~100m to ~350m) as the vehicle count was increased from 5,000 vehicles/ hour to 6,000 vehicles/ hour. The AMQL increment for 6,000 vehicles/hr to 8,000 vehicles/ hour was comparatively steady for *AV-Mod2* and *AV-Mod1* driving behaviours at ~17% and ~49% respectively but was significantly higher for *AV-Normal* and *AV-Aggressive* driving behaviours, at ~66% and ~85%.

Also, both *AV-Normal* and *AV-Aggressive* driving behaviours were unable to cope with traffic flow greater than 8,000 vehicles/hour and AMQL was ~1750m on average. In contrast, the analysis of AMQL on N06 showed that 6,000 vehicles/hour is the tipping point and average queue length is ~500m. With traffic flow greater than 7,000 vehicles saturates the flow on N06 as the AMQL is ~600m, the full length of N06. The reason for this could be the higher proportion of conventional *Cars* on A206 roads which navigates via N06 to travel through the tunnel. The analysis clearly shows that by reducing the headway and standstill distance does improve the congestion given the concentration of CAV-F vehicles in a mix of conventional vehicle is considerably higher, as in the case of A282 road section where ~21% of vehicles were simulated as *CAV-F*. Also, the infrastructure limit mentioned in the report [104], aligns with the finding which stated that a four-lane road network should be able to support 7,000 or more vehicles per hour.

#### 3.5.3.2. Driving Behaviour Changes – Travel Time Analysis

Figure 18 shows the plot of average travel time over 10 simulation runs of individual vehicle counts and driving behaviours.

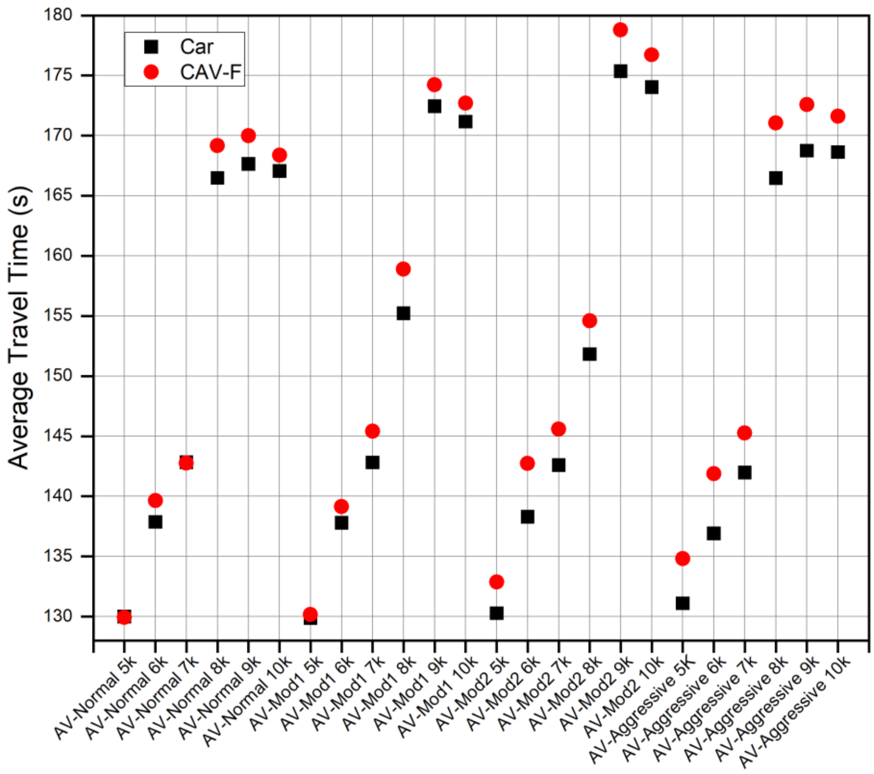


*Figure 18 Average Travel Time (ATT) for varying vehicle counts and driving behaviours*

By analysing the ATT for within the groups, a Kruskal-Wallis test was conducted to determine the difference in ATT within all the driving behaviours. The test showed that for all the driving behaviours the ATT within varying traffic flows was statistically significantly different, *AV-Normal* $X^2$ *(5) = 294.07, p < 0.005, AV-Mod1* $X^2$ *(5) = 305.77, p < 0.005, AV-Mod2* $X^2$ *(5) = 305.03, p < 0.005* and *AV-Aggressive* $X^2$ *(5) = 286.43, p < 0.005*. For *AV-Normal*, the pairwise comparisons are presented in Table 24.

Table 24 *AV-Normal* driving behaviour pairwise comparison withing group

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **5K-6K** | -65.381 | 0.007* |
| **5K-7K** | -106.261 | 0.000* |
| **5K-8K** | -229.925 | 0.000* |
| **5K-9K** | -232.649 | 0.000* |
| **5K-10K** | -232.649 | 0.000* |
| **6K-7K** | -40.880 | 0.433 |
| **6K-8K** | -164.544 | 0.000* |
| **6K-9K** | -167.268 | 0.000* |
| **6K-10K** | -167.268 | 0.000* |
| **7K-8K** | -123.664 | 0.000* |
| **7K-9K** | -126.388 | 0.000* |
| **7K-10K** | -126.388 | 0.000* |
| **8K-9K** | -2.724 | 1.000 |

| | | |
|---|---|---|
| **8K-10K** | -2.724 | 1.000 |
| **9K-10K** | 0.000 | 1.000 |

For *AV-Mod1*, the pairwise comparisons are presented in Table 25.

Table 25 *AV-Mod1* driving behaviour pairwise comparison withing group

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **5K-6K** | -66.517 | 0.005* |
| **5K-7K** | -109.280 | 0.000* |
| **5K-8K** | -174.496 | 0.000* |
| **5K-10K** | -251.496 | 0.000* |
| **5K-9K** | -258.410 | 0.000* |
| **6K-7K** | -42.763 | 0.334 |
| **6K-8K** | -107.979 | 0.000* |
| **6K-10K** | -184.979 | 0.000* |
| **6K-9K** | -191.893 | 0.000* |
| **7K-8K** | -65.216 | 0.008* |
| **7K-10K** | -142.216 | 0.000* |
| **7K-9K** | -149.129 | 0.000* |
| **8K-10K** | -77.000 | 0.001* |
| **8K-9K** | -83.914 | 0.000* |
| **10K-9K** | 6.914 | 1.000 |

For *AV-Mod2,* the pairwise comparisons are presented in Table 26.

**Table 26** *AV-Mod2* driving behaviour pairwise comparison withing group

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **5K-6K** | -72.862 | 0.001* |
| **5K-7K** | -98.267 | 0.000* |
| **5K-8K** | -162.983 | 0.000* |
| **5K-10K** | -249.819 | 0.000* |
| **5K-9K** | -261.491 | 0.000* |
| **6K-7K** | -25.405 | 1.000 |
| **6K-8K** | -90.121 | 0.000* |
| **6K-10K** | -176.957 | 0.000* |
| **6K-9K** | -188.629 | 0.000* |
| **7K-8K** | -64.716 | 0.008* |
| **7K-10K** | -151.552 | 0.000* |
| **7K-9K** | -163.224 | 0.000* |
| **8K-10K** | -86.836 | 0.000* |
| **8K-9K** | -98.509 | 0.000* |
| **10K-9K** | 11.672 | 1.000 |

Finally, for *AV-Aggressive*, the pairwise comparisons are presented in **Table 27**.

**Table 27** *AV-Aggressive* driving behaviour pairwise comparison withing group

| Sample 1-Sample 2 | Test Statistic | Adjusted Significance |
|---|---|---|
| **5K-6K** | -52.915 | 0.068 |
| **5K-7K** | -95.716 | 0.000 |
| **5K-8K** | -217.561 | 0.000 |
| **5K-10K** | -224.880 | 0.000 |
| **5K-9K** | -228.449 | 0.000 |
| **6K-7K** | -42.801 | 0.332 |
| **6K-8K** | -164.646 | 0.000 |
| **6K-10K** | -171.965 | 0.000 |
| **6K-9K** | -175.534 | 0.000 |
| **7K-8K** | -121.845 | 0.000 |
| **7K-10K** | -129.164 | 0.000 |
| **7K-9K** | -132.733 | 0.000 |
| **8K-10K** | -7.319 | 1.000 |
| **8K-9K** | -10.888 | 1.000 |
| **10K-9K** | 3.569 | 1.000 |

By analysing the ATT for between the groups, a Kruskal-Wallis test was conducted to determine the difference in ATT between all the driving behaviours. The test showed that for all the driving behaviours the ATT between varying traffic flows was statistically significantly different $X^2$ *(3) = 27.13*, *p < 0.005*. The pairwise comparisons were performed using Dunn's (1964) procedure. The post hoc analysis revealed statistically significant similar ATT between *AV-Normal* and *AV-Mod1* (*p = 1.000*) and between *AV-Mod2* and *AV-Aggressive* (*p = 1.000*), and was not similar for all other group combinations.

The analysis showed that average travel time pattern is similar to AMQL plot. Further analysis showed that *AV-Mod1* and *AV-Mod2* driving behaviours were statistically similar and *AV-Normal* and *AV-Aggressive* were statistically similar. It was observed that 8,000 vehicles/hour was the tipping point and travel time was increased by ~8% (11 seconds) for *AV-Mod1* and *AV-Mod2* driving behaviours and by ~18% (25 seconds) for *AV-Normal* and *AV-Aggressive* behaviours on per vehicle basis. The increase of ~6% was also observed for all the driving behaviours when vehicle count was incremented from 5,000 vehicles/ hour to 6,000 vehicles/ hour.

The results also showed that the average travel time for *CAV-F* vehicle category was always slower than conventional *Car* category. On average, for *AV-Normal* the difference was ~1.5 seconds, for *AV-Mod1* ~2 seconds, for *AV-Mod2* ~3 seconds and for *AV-Aggressive* driving behaviour ~4 seconds. It is interesting to observe that even with AMQL ranging between ~100m to ~2, 000m, the total average travel time for all different traffic flows is just under 3 minutes, which is approximately the average travel time for ~4 km (2.5 mi) A282 road section towards Dartford Crossing tunnel at 80 km/h (50 mph). This could imply that although the longer queues are formed, they are cleared quickly not leading to prolonged congestion and with shorter headway, standstill distance and scope of connected vehicles, traffic was able to travel faster.

#### 3.5.3.3. Traffic Speed – AMQL Analysis

Figure 19 shows the AMQL plot for varying speed limits.

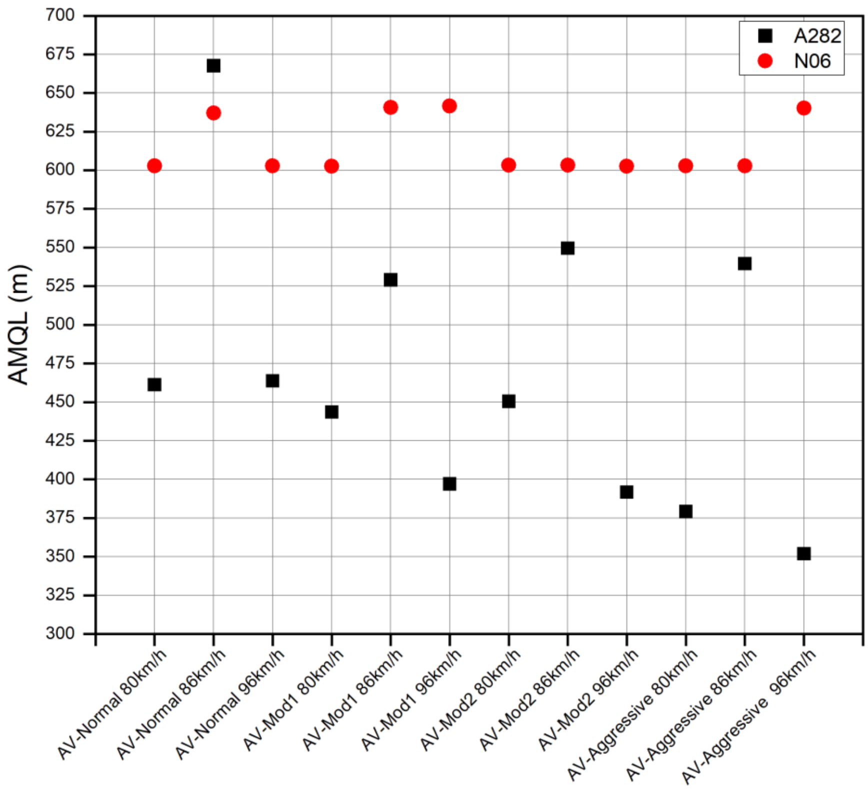


*Figure 19 AMQL for fixed vehicle count & varying speed limits for different driving behaviours*

The analysis showed that, interestingly the 86 km/hour (55 mph) speed limit scenario performed worse than 80 km/hour (50 mph) and 96 km/hour (60 mph) speed limits for all driving behaviours, for both A282 and N06 road sections. On A282, for *AV-Mod1* and *AV-Mod2* the 86 km/hour speed limit scenario was ~24% worse and for *AV-Normal* and *AV-Aggressive* the speed limit was ~38% worse than the other two scenarios. On N06 road section, all the driving behaviour and all varying speed limits proved unsuccessful in easing AMQL, probably due to low percentage of CAV-F vehicle composition. In particular, the *AV-Normal* 80 km/hour, *AV-Mod1* 86 km/hour, *AV-Mod1* 96 km/hour, and *AV-Aggressive* 96 km/hour simulation scenarios performed ~6% worse than rest of the scenarios, which were statistically similar. It was also observed that for all driving behaviour except for *AV-Normal* the AMQL improved at 96 km/hour (60 mph) speed limit by ~7.5% from 80 km/hour (50 mph). The *AV-Mod2* driving behaviour performed best with an improvement of ~13% in improving AMQL.

### 3.5.3.4. Traffic Speed – Travel Time Analysis

Figure 20 shows the analysis of average travel time for varying speed limits.

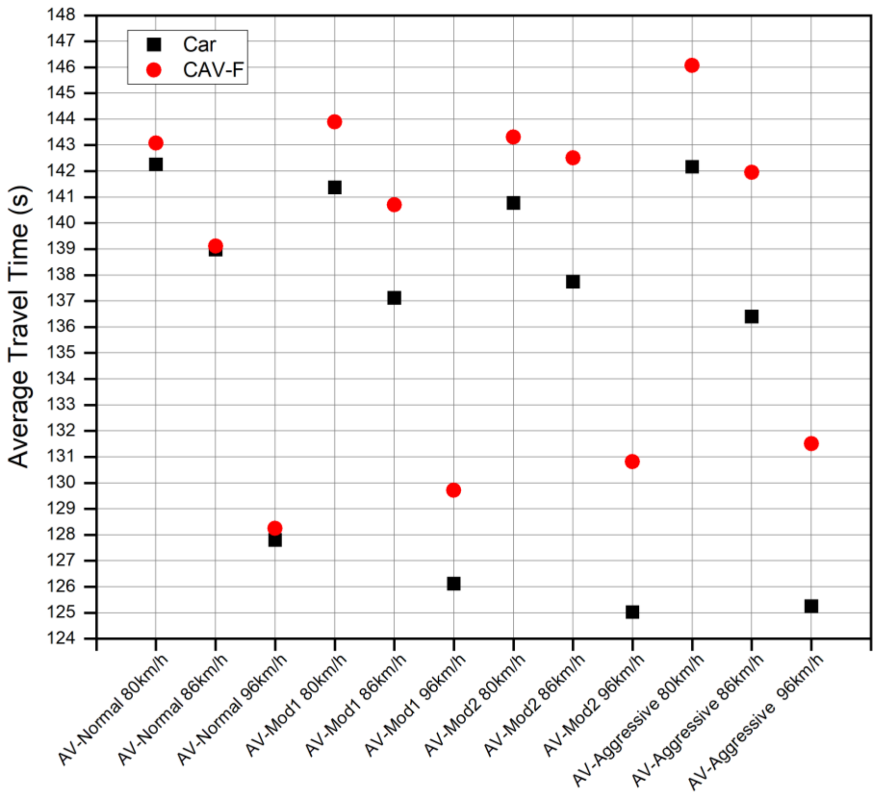


*Figure 20 Average travel time plot for fixed vehicle count and varying speed limits for different driving behaviours*

The results showed that all the driving behaviours were able to reduce average travel time as the speed limit was increased from 80 km/hour (50 mph) to 96 km/hour (60 mph). Comparing the *Car* and *CAV-F* vehicle categories, the biggest improvement was observed for *Car* vehicle category, especially for *AV-Mod1* with ~2.5%, *AV-Mod2* with ~3% and *AV-Aggressive* with ~4% improvement in average travel time. For *AV-Normal* driving behaviour the improvement between the two vehicle categories was small with ~0.3%.

Analysis also showed that, although with the increase in speed limit the average travel time was improved, the changes in driving behaviours from *AV-Normal* to *AV-Aggressive* were counterproductive for *CAV-F* vehicle category. A linear increase in average travel time was noted when the headway and standstill distance were reduced, and scope of connectivity was increased, especially for 96 km/hour (60 mph) speed limit scenario.

## 3.6. Conclusions

From the results, it can be deduced that the two hypotheses of the study hold true and in general CAV-F implementations have reduced the traffic congestion and delay. It is interesting to observe the mixed impact of AVs on queue formations and travel times, especially for *AV-Aggressive* driving behaviour which was significantly different in comparison to *AV-Cautious* and *AV-Normal* scenarios. It was noted that by only replacing conventional DGVs and ALVs categories to CAV-F, significant improvements were achieved in reducing the travel time and road traffic queues. However, the aggressive implementation of CAV-F was rather counterproductive. Thus, a careful approach would be required in determining the driving parameters according to traffic conditions and road infrastructure to make the best use of CAV-F technology. The study emphasised on importance of connectivity for CAV and showed that if valid V2I communications were established, they could help reduce or eliminate the requirement of closing the tunnels for check and allow procedures. This could in-turn benefit the supply chain for freight and hauler companies by increasing their productivity and turnaround journey time.

The impact of simulated CAV-F in improving the traffic throughput at Dartford Crossing tunnel was also studied. The results supported the hypothesis and the reduction in headway, standstill distance and increase in scope of connectivity does help improve the traffic throughput. Using *AV*-Mod2 driving behaviour, the Dartford Crossing tunnel road infrastructure would be able to support up to 7,000 vehicles/hr with ~500 m average queues. In contrast, though the increase in speed limit was observed to be productive, the impact on CAV-F vehicle category was negative. To summarise, the analysis of simulation results confirms the advantages of using CAV-F transportation in increasing the traffic flow at the tunnel.

# Chapter 4

# Dynamic Gap Generation Model

As it has been established in Chapter 3 that the CAV-F vehicles have been proven successful in improving road congestion, travel time and traffic throughput in a road tunnel environment, the next logical step is to determine how the CAV-F vehicles would be informed and coordinated using C-ITS communications to maximise the benefits of safe and secure transit of DGVs and ALVs via the tunnel.

This chapter aims at automating the escorting procedures at the road tunnels on the TEN-T (not just specific to Dartford Crossing tunnel), as per ADR regulations by dynamically generating vehicular gaps between the platoon of CA-DGVs vehicles and their preceding and following vehicles. A novel mathematical model is defined to identifying optimal geo-referenced locations for C-ITS communications which would enable the generation of dynamic vehicular gaps between the CA-DGVs and their preceding and following vehicles, such that they could travel via a tunnel as a platoon in isolation or at a pre-determined safe distance to ensure maximum road safety.

## 4.1. Literature Review

Previous research [96] has discussed the tunnel safety improvements using C-ITS solutions. It mentioned cooperative systems such as CIVS (Cooperative Vehicle-Infrastructure Systems) and SMARTFREIGHT projects which helped develop Cooperative Tunnel Management application, targeting at the road tunnel safety. The tunnel management application detailed how V2I would be used in determining the compliant and non-compliant DGVs and how this information could be displayed on in-vehicle Human Machine Interface (HMI) for the driver to take appropriate actions, such as either drive through the tunnel, hold for verification or find an alternative route as access was not permitted via the tunnel. The application used both centralised and decentralised approaches in effectively monitoring and coordinating DGVs in the tunnel. Another tunnel safety report [120] focused on HGVs in the tunnel detailed the benefits of using C-ITS communications in providing safe travel via a tunnel.

A report on Stockholm Bypass Tunnel [97] also mentioned the use of C-ITS solutions for emergency management, avoiding standstill vehicles and managing DGVs when travelling through a road tunnel environment. The paper proposed the use of dynamic truck lanes for DGVs to improve their movement and safety in the tunnel, with a prerequisite of established V2I communications. Similar to the SMARTFREIGHT project, the movements of DGVs at Dartford-Thurrock River Crossing Tunnel are also controlled and monitored as per ADR and additional regulation [121, 122]. The DGVs arriving at the tunnel are inspected for their carriage and only compliant vehicles are allowed to travel via the tunnel. They are queued and multiple vehicles are escorted together in isolation of other road vehicles via the tunnel, for cost effective measures. The system does not use dynamic coordination between DGVs and other road vehicles to optimise their movement but is based on semi-automated sensors to detect and monitor road traffic. The two separate papers [82, 83] focused on improving the traffic flow at the Dartford Crossing Tunnel using CAV DGVs and freight vehicles highlighting the benefits on reduced congestion and delays which would in turn have socio-economic benefits.

In a separate paper [123], again based on Stockholm Bypass Tunnel presented the global and local dynamic coordination approaches between DGVs using C-ITS communications. This would be enabling them to negotiate and plans their arrivals at the tunnel to mitigate accident scenarios by determining safer headways when they approach the tunnel from different road sections. Although the above study mentions about dynamic coordination of DGVs by utilising real-time vehicles speed, GPS location, etc., it was limited to synchronising DGVs to avoid crashing but still traveling alongside other vehicles. The study does not cater for vehicle which would need escorting and determines the control area arbitrarily for global coordination. The GOOD ROUTE project [124] was aimed at developing a coordinated system for DGVs routing, monitoring, enforcement and driver support using dynamic and real-time data via V2V and V2I communications. One of the project's pilot sites was 17 km long Gotthard Road Tunnel in Switzerland which was used to demonstrate basic routing decisions and clearance to pass. The main difference identified between the approach mentioned in this chapter and GOOD ROUTE project is that the latter provided the coordinated information to the DGVs drivers or the operations to follow the prescribed route or course of action, whereas in this study the focus is on dynamically controlling the coordinated movements of DGVs by modulating the traffic speeds.

To ensure CAV-F vehicles are able to manage the safe passage via a road tunnel network, it is imperative that the vehicles and infrastructure behave symbiotically and V2V and V2I communications are relayed at appropriate time and at appropriate location to optimise the coordination. The traffic control using Variable Speed Limits (VSL) and Coordinated ramp metering was studied [125] to create a discharge section upstream of the congested section to support efficient traffic flow. In study [98], the scenarios of mixed traffic using CAV to improve traffic capacity was studied but was limited by smaller vehicle counts and using platoons on a single-lane. In addition to improving tunnel safety and communication protocols, controlling the flow of traffic and congestion prevention is also necessary. Measures such as Active Traffic Management [126] systems, Ramp Metering [127, 128], Dynamic Ramp Metering [129] for controlling the traffic on slip roads based on near real-time Motorway Incident Detection and Automatic Signalling (MIDAS) data [106] to merge on main carriageway during rush hours, VSL [130, 131], ITS [132] etc., are widely used as traffic control measures by transport authorities to control and monitor the traffic flow. The evaluation of different smart motorway schemes was conducted [133, 134] and it was shown that they are effective in controlling the traffic flow than the non-managed motorways. The Smart Motorways CALibration and Optimisation (SMCALO) toolkit [135-137] is used by smart and managed motorway schemes in the UK in determining the flow threshold in near real-time based on MIDAS historic data, to set VSL on motorways controlling congestions and traffic shockwaves. Additionally, other studies have discussed the path-planning and collision avoidance measures for autonomous vehicles [138-141].

By reviewing different traffic control and C-ITS techniques for conventional and connected vehicles, to the best of the authors' knowledge no study has so far proposed a model to appropriately identify geo-reference location for C-ITS communication to let platoons to travel in isolation or buffer safety gap via a tunnel.

## 4.2. Motivation

The above-mentioned studies and tunnel management procedures do point out the benefits of dynamic and coordinated movements of DGVs in improving the efficiency and safety of travel via a road tunnel but lacks the solution which would mathematically help identify following two objectives:

1. Geo-reference locations for C-ITS communications to enable the dynamic coordination of DGVs' approaching a tunnel.
2. Vehicular gaps between DGVs and other road vehicles such that DGVs platoons could travel via the tunnel in isolation.

The motivation for the first objective is that, to the best of authors knowledge, no work is carried out in identifying optimal reference locations for C-ITS communications when trying to dynamically coordinate movement of vehicles. Although the paper [142] provides an insight on the various C-ITS communications projects in European Union (EU), highlighting services ranging from Emergency electronic Braking Light (EBL) to Connected and Cooperative Navigation (CNN), and Directive 2010/40/EU [143] layout guidelines for deployment of Intelligent Transportation Systems (ITS) in field, none of these are able to determine the distance or location for optimal communications to be established for coordinating the movements of similar groups of vehicles, in this case DGVs, travelling on same or separate road sections.

Another important point to consider is that, all of the various C-ITS communication services are implemented using standardised V2V and V2I messages such as using Cooperative Awareness Message (CAM) [144], Decentralized Environmental Notification Message (DENM) [145], Signal Phase and Timing (SPaT) and Map Data (MAP) [146-148] and using suitable communication technologies such as ETSI ITS G5 [149] and cellular LTE [150] and 5G [151], allowing independence between the communication protocols. Similarly, the mathematical model proposed in this chapter is considered to be independent of communication protocols and the C-ITS architectural details for the model are beyond the scope of this paper. The pros and cons of using V2V and V2I communication strategies were highlighted in paper [152]. To realise full potential of the proposed novel mathematical model, the infrastructure should be established based on the current and future best practices of message delivery and communication technologies. By using the combination of centralised and decentralised approaches, where V2V could be used, as an example, to maintain safe distances amongst vehicles, and V2I could be used to confirm and verify the vehicle's compliance for the approaching tunnel, well in advance to make appropriate adjustments to its journey route.

The motivation for the second objective is based on, the tunnel safety and DGVs movement restrictions detailed in ADR regulations [153] and Directive 2004/54/EC [154], and on the cost associated to parking and escorting procedures for both the road tunnel and freight management systems. As an example, by analysing the real-world traffic flow data at Dartford Crossing tunnel, it was observed that escorting of DGVs was a regular occurrence with an average of four escorts per hour. The total average time spend for inspection and escorting of DGVs was 30 min with an upper bound of ~5 hrs. During this time cost associated to parking and holding vehicles could be high for both tunnel operators and freight companies. The studies suggest [30, 82, 122] that while escorting is in progress, the traffic stopped from traveling via tunnel could lead to increase in congestion, delays and socio-economic impacts.

## 4.3. Methodology

The objective of the study is to allow a safe passage to the platoon of CA-DGVs, referred to as the '*convoy*' in the paper, via a road tunnel in an isolation. The proposal is to create vehicular gaps between the *convoy* and its *preceding* and *following* vehicles without stopping the road traffic but by dynamically modulating the speeds of *preceding*, *convoy* and *following* vehicle groups. Here the *preceding* vehicles are defined as vehicles travelling in-front or alongside the *convoy*, and the *following* vehicles are defined as vehicles traveling behind the *convoy*.

To achieve the desired objective, a novel mathematical model is detailed to identify geo-reference point locations $(rP)$ at which the V2I communication would be established to dynamically coordinate DGVs by adjusting their speeds such that desired vehicular gaps are created between the *preceding*, *convoy* and *following* vehicle groups. The calculations for generating vehicular gaps are categorised into two categories based on the tunnel's length:

- *Category 1*: For shorter tunnels or tunnels with additional requirements to escort DGVs in isolation of other traffic such as Dartford Crossing tunnel, the gap should be equal to the tunnel's length plus safety distance between *preceding*, *convoy* and *following* vehicle groups.
- *Category 2*: For longer tunnels such as Mont Blanc or Gotthard road tunnels, the gap between the vehicle groups should be determined based on tunnel safety guidelines ensuring appropriate distance is maintained such that in case of an incident, both *preceding* and *following* vehicles have enough time to evacuate the tunnel ensuring the safety of other road users.

The study classifies a tunnel in *Category 1* if the length is under 3 kilometres and *Category 2* otherwise. This assumes that longest length required for *Category 1* would be equal to,

$$L_{category1} = \left(g_{preced} + g_{follow}\right) + \sum_{i=1}^{n}\left(l + d_{stop}\right) \qquad (5)$$

where $L_{category1}$= *Category 1* maximum tunnel length, $g_{preced}$ = vehicular gaps between *preceding* and *convoy*, $g_{follow}$ = *convoy* and *following* vehicles, *l* = *CA-DGVs* length, $d_{stop}$ = safe stopping distance between *CA-DGVs* travelling together and *n* = number of vehicles in convoy.

The $g_{preced}$ and $g_{follow}$ are defined as two separate variables because to optimise the traffic flow via a tunnel, shorter gap could be determined between *convoy* and *preceding* vehicles then *following* vehicles, as in case of an incident *preceding* would be able to drive themselves out of tunnel safely as driving ahead.

Using (5) and assuming normal travel conditions, with maximum potential values for each of the variables as, $g_{preced}$ = $g_{follow}$ = 1,000m (assumed), *l* = 18.75m [155], $d_{stop}$ = 108m @ 60mph [156], *n* = 5 [74], the calculated $L_{category1}$ = ~2,559m.

To support with a real-world tunnel scenario, at two Mersey Tunnels of length 2.4 kms and 3.2 kms respectively, the DGVs are escorted by traffic police maintaining a distance of 100m between their preceding and following vehicles [157]. This may not be based on the assumptions mentioned for equation (5) in this chapter. Determining the safety distances in both the scenarios is beyond the scope of this paper but should be based on geometry, length, type of vehicle, dangerous good carriage, weather conditions, etc.

To ensure the dynamic gaps are effectively created, the dynamic speed changes are applied to the road traffic that is downstream from the primary reference point location $(rP_{primary})$and the destination tunnel. The study identifies $rP_{primary}$ as the first geolocation on the main road at which dynamic speed limits are enforced to the three vehicle groups. The idea is, if the *preceding* vehicles retains the mandatory speed $(v)$ and the speeds for the *convoy* and the *following* vehicles are reduced by $x$ and $x'$% of mandatory speed limit respectively, such that $v_{prcedeing} > v_{convoy} > v_{follow}$, then over a given distance $d$ desired gaps will be generated between the groups. This will allow the *convoy* to enter the tunnel when the *preceding* vehicles are exiting it, and once the *convoy* has exited the tunnel *following* vehicles begin to enter the tunnel. In order to achieve this, there is a need to calculate the distances *d* and $d'$ from the tunnel, at which the speeds of the *convoy* and the *following* vehicles are adjusted, respectively. The $rP$ is then positioned at the $max(d, d')$ from the entrance of the tunnel. It is important to note that the dynamic speed change for the *following* group will only applied when the last vehicle in the *convoy* crosses the given $rP$ locations. But all the vehicles in the *convoy* must update their speeds as soon as they cross the $rP$ locations. This would ensure that neighbouring vehicles to the *convoy* reduce their speed in a safe manner and faster moving vehicles are not blocked by the slower vehicles. Here a set is defined as $B = \{convoy, following\}$ for the categories requiring $rP$ locations to be calculated. To ensure shortest possible delays is achieved when entering and existing the tunnel between the vehicles' groups, the model itself would not be sufficient due to traffic perturbations and would require timely setting and resetting of dynamic speed limits.

The study is focused on the UK motorways and associated A-roads leading to a road tunnel on TEN-T road network with ADR regulations under normal driving conditions without any accidents or incidents. For accurately identifying primary and subsequent geo-referenced locations, it is important to determine number of slip roads and mandatory speed limit between $rP_{primary}$ and the destination tunnel. On their basis a suitable mathematical formulation would be applied. The UK motorways design and junction road layouts were briefly reviewed [158, 159] but as the model is only concerned with approaching road(s) and speed limit(s) downstream of $rP_{primary}$, detailed analysis of the design is beyond the scope of this paper.

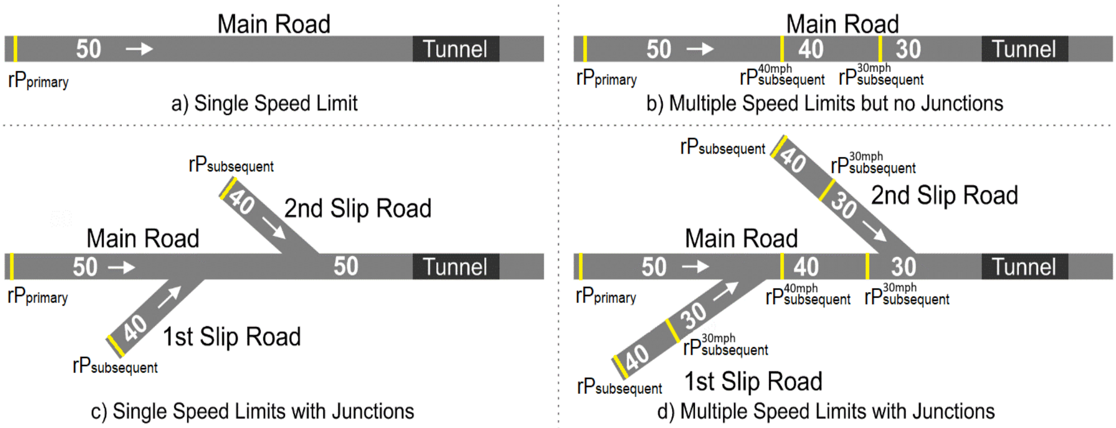


*Figure 21 Road layout scenarios as observed between calculated rP location(s) and the target tunnel*

Depending on the position of $rP_{primary}$ following road layout scenarios are identified:

1. $rP_{primary}$ is positioned before the first nearest approaching junction to the tunnel and without further downstream mandatory speed changes, as in Figure 21 (a).
2. $rP_{primary}$ is positioned before the first nearest approaching junction to the tunnel and with additional downstream mandatory speed limits, as in Figure 21 (b).
3. $rP_{primary}$ is positioned on the main road which has one or more approaching junctions between it and the tunnel. No additional mandatory speed limits are identified downstream of $rP_{primary}$ on main road and $rP_{subsequent}$ on associated junctions but have different speed limits on individual road sections, Figure 21 (c).
4. $rP_{primary}$ is positioned on the main road which has one or more approaching junctions between it and the tunnel. Also, additional mandatory speed limits are

identified downstream of $rP_{primary}$ on main road and $rP_{subsequent}$ on associated junctions, as in Figure 21 (d).

Furthermore, for road layouts with additional slip roads, there are two different driving scenarios where:

- A single convoy is travelling on the main road.
- Multiple convoys are travelling on different roads and should be merged as one before entering the tunnel.

For the mentioned two tunnel categories, four road layout scenarios and two driving scenarios, mathematical formulas are derived to ensure the *convoy* travels via a tunnel with appropriate gaps between *preceding, convoy* and *following* vehicle groups, irrespectively.

## 4.4. Mathematical Model

A mathematical model is detailed below to identify appropriate $rP$ at distance $d$, at which the speeds would be adjusted to achieve desired gaps**.**

### 4.4.1. Primary Reference Location (All Road Layouts)

The first $rP$ identified is be termed as $rP_{primary}$**.** This reference point is crucial in determining if there will be a need for subsequent reference points ($rP_{subsequent}$) or not. For a road layout scenario which have no additional mandatory speed limits or junctions between the $rP_{primary}$ and the destination tunnel**,** there the $rP_{primary}$ location would be sufficient to generate desired gaps. In cases where there are additional mandatory speed changes on junctions or between the $rP_{primary}$ and the tunnel, then $rP_{subsequent}$ locations will be required to ensure the gaps are appropriately generated when the speeds vary or additional traffic is merged with the main road. The desired gap is defined as,

$$g = (L_{tnl} + L_{convoy} + d_{safe}) \tag{6}$$

where, $L_{tnl}$ is the length of the destination tunnel, $L_{convoy}$ is the length of the *convoy* and $d_{safe}$ is the safety distance between *convoy* and two other groups. Detailed analysis of $d_{safe}$ parameter is beyond the scope of this paper and should be identified using methods such as quantitative risk analysis for tunnels [160-162]. Although, at Dartford Crossing tunnel, to optimise the escort and minimise traffic disruptions, the Highways England traffic officers (HATO) communicate to start escorting as the last of preceding vehicles exit the tunnel and release of the normal traffic into tunnel as the last of escorting vehicles exist the tunnel.

$L_{convoy}$ is calculated as,

$$L_{convoy} = \sum_{j=1}^{n} \left(l + d_{stop}\right)_j \quad (7)$$

where *l* = length of vehicle in the *convoy* of size *n*, $d_{stop}$ = safe stopping distance between *j* and *j-1* within *convoy*.

It is important to consider the *convoy's* length in calculating desired gap $g$, to ensure the *preceding* vehicle travelling alongside the last vehicle in the *convoy* (on multi-lane road network), could safely overtake the *convoy* before further speed changes are applied at $rP_{subsequent}$ (where applicable).

Using (6), the time $t$ required to generate a gap *g* is calculated for $b \in B$ as,

$$t_b = \frac{g}{v_{diff}}, \begin{cases} v_{diff}, \ (v_i - (v_i - x)) > 0 \\ 0 < x < v_i \end{cases} \quad (8)$$

where $v_i$ = velocity of leading vehicle group, $v_f$ = reduced velocity by *x%* of $v_i$.

Additionally, deceleration time take by vehicles to reduced speed is calculated as,

$$t_{\vec{a}} = \left(\frac{(v_f - v_i)}{\bar{a}}\right) \quad (9)$$

where $t_{\vec{a}}$ = deceleration time and $\bar{a}$ = average acceleration.

Adding (9) to (8),

$$t'_b = \left(\left(\frac{g}{v_{diff}}\right) + |t_{\vec{a}}|\right) \quad (10)$$

The distance *d* at which $rP_{primary}$ would be positioned for *b* is calculated as,

$$d_b = (v_i \times t'_b) + \delta \quad (11)$$

where, $\delta$ is the latency for C-ITS communications.

Using (11), $rP_{primary}$ is calculated as,

$$rP_{primary} = max(d_b) \quad (12)$$

where primary geolocation is selected by choosing the maximum of distance values for the *convoy* and the *following* groups. This is to ensure that vehicles slow down safely and faster moving vehicles are not blocked by slower traffic.

### 4.4.2. Subsequent Reference Locations

The subsequent reference locations ($rP_{subsequent}$) are required in addition to the $rP_{primary}$, for all other road layouts except for the layout defined in Figure 21 (a).

#### 4.4.2.1. Multiple Speed Limits on Single Road

For the layouts with no junctions but with additional mandatory speed changes between $rP_{primary}$ and the tunnel, $rP_{subsequent}$ are required such that when the group of preceding vehicles enter a new speed limit zone, the convoy and following vehicles' speeds are adjusted accordingly, to ensure the gaps keep expanding at determined rate. The $rP_{primary}$ for this layout is calculated using (12).

To calculate the $rP_{subsequent}$ location, first calculate the time $t_{preced}$ to determine how long it will take for the *preceding* vehicles to reach the next speed change for $\forall\ j \in SN$ where $SN$ is number of additional speed changes between $rP_{primary}$ and the tunnel as,

$$t^{j}_{preced} = \left(\frac{d'_{speedChng}}{v_{preced}}\right)_{j} \tag{13}$$

where $d'_{speedChng}$ = distance between $rP_{primary}$ (or immediate previous $rP_{subsequent}$ location) and the next mandatory speed change, $v_{preced}$ = current speed of *preceding* vehicles.

Using (13), the distances $d$ at which $rP_{subsequent}$ is positions for $b \in B$ and for all speed changes are calculated as,

$$d^{j}_{b} = \left(v_b \times t^{j}_{preced}\right) + (l + \varepsilon) + \delta \tag{14}$$

where *l* = length of the last vehicle in *convoy*, $\varepsilon$ = small constant added to the length *l* to ensure if a vehicle from *preceding* group was travelling alongside vehicle *l*, has enough time to cross the subsequent mandatory speed limit before it is been adjusted by the vehicle *l.*

Using (14) $rP_{subsequent}$ for all speed changes is calculated as,

$$rP^{j}_{subsequent} = max\left(d^{j}_{b}\right) \tag{15}$$

The $rP_{subsequent}$ location is then positioned from the $rP_{primary}$ or the immediate previous $rP_{subsequent-1}$ location.

### 4.4.2.2. Multiple Junctions with Single Speed and a Convoy

For the road layout with multiple junctions between $rP_{primary}$ location and the tunnel, $rP_{subsequent}$ locations will be required for $\forall\, j \in JN$ where $JN$ is number of junctions between $rP_{primary}$ location and the tunnel. Two $rP_{subsequent}$ locations per junction are required to be determined for a scenario where a single convoy is travelling on the main road. The first reference point for updating the speed ($rP_{subsequent}^{updateSlip}$) will be on the main road where the convoy is travelling, as the dynamic speed changes will only be trigged by the last vehicle in the convoy. The second reference point ($rP_{subsequent}$) will be positioned on the slip road, where the speed changes would be applied, when trigged via $rP_{subsequent}^{updateSlip}$ reference point.

The aim is for the *preceding* vehicles on slip roads to merge with the *preceding* vehicles on the main road and *following* vehicles on slip roads with the *following* vehicles on the main road, with an appropriate gap for the *convoy* to squeeze in between two groups, maintaining generated gaps.

To determine the $rP_{subsequent}$ for the slip roads, first calculate the time $t_{preced}$ taken by preceding vehicles on the main road to reach all the junctions as,

$$t_{preced}^{j} = \left(\frac{\left(d'_{junc} + L_{convoy}\right)}{v_{preced}}\right)_{j} \tag{16}$$

where $d'_{junc}$ = distance between $rP_{primary}$ and junction $j$.

Once $t_{preced}$ is calculated, determine the distance travelled by the *following* vehicles $d_{followTravelled}$ on the main road in $t_{preced}$ as,

$$d_{followTravelled}^{j} = \left(v_{follow} \times t_{preced}^{j}\right) \tag{17}$$

where $v_{follow}$ = current speed of the *following* vehicles.

Using (17), calculate the gap $g$ developed between the *convoy* and the *following* vehicles for all the junctions as,

$$g_j = \left(d_{followTravelled} - d_{follow}\right)_j \tag{18}$$

The distance $d$ for $b \in B$, for all the junctions is calculated as,

$$d_b^j = \left(v_b \times \left(\frac{g_j}{v_{diff}}\right)\right) \tag{19}$$

Using (19) $rP_{subsequent}$ is calculated as,

$$rP_{subsequent}^{j} = max(d_b)_j \tag{20}$$

Now $rP_{subsequent}^{updateSlip}$ locations for all the junctions are calculated by adding deceleration distance and subtracting the time lag distance $d_{lag}$ (caused due to differences in mandatory speed limits between main and slip roads) to the $rP_{subsequent}$ distance for individual slip roads. First calculate the time lag between main road and subsequent junctions as,

$$t_{lag}^{j} = \left(\frac{\left(d'_{junc}\right)_j}{v_{mainRoad}}\right) - \left(\frac{\left(d'_{junc}\right)_j}{v_{slipRoad}^{j}}\right) \tag{21}$$

where $v_{mainRoad}$ = mandatory velocity on main road, $v_{slipRoad}^{j}$ = mandatory velocity on slip road for junction *j*. Note, for scenarios where all road sections have exact mandatory speed limits, $t_{lag} = 0$.

Using (21), distance $d_{lag}^{j}$ is calculated as,

$$d_{lag}^{j} = \left(v_{mainRoad} \times t_{lag}^{j}\right) + \delta \tag{22}$$

Deceleration distance is calculated using (9) as,

$$d_{\vec{a}}^{j} = \left|\left(v_f \times \ (\mu \times t_{\vec{a}})\right)\right| \tag{23}$$

where $v_f$ = final velocity of slowed down vehicle group and $\mu$ = number of times the speed is reduce on the slip. Here, $\mu$ will be equal to 2 as on the slip with single mandatory speed limit, vehicles will slow down at $rP_{subsequent}$ and at merging junction, in a normal traffic flow.

Adding (23) to (20) and subtracting (22) gives,

$$\left(rP_{subsequent}^{updateSlip}\right)_j = \left(rP_{subsequent}\right)_j + d_{\vec{a}}^{j} - d_{lag}^{j} \tag{24}$$

The calculated $rP_{subsequent}^{updateSlip}$ in (24) is positioned on the main road at distance measured downstream from the respective junctions.

#### 4.4.2.3. Multiple Junctions and Convoys but Single Speed

The road layout with multiple junctions have an alternate scenario whereby separate convoys would be travelling on different roads throughout the network, and to be merged as one before travelling through the tunnel. To ensure all separate convoys are coalesced as one platoon at their respective junctions, it is important to satisfy following conditions:

- The coalesced *convoy* length must not exceed the predetermined maximum limit of vehicles in a platoon. The vehicle groups must be travelling such that each of the groups on main road must arrive at the junction at the same time as their counterparts on the slip roads. This should consider the speed differences between the main road and slip road, and of any speed changes applied at $rP_{primary}$ and $rP_{subsequent}$ geolocation. For example, if the mandatory speed limit on slip road is slower than the main road, then the *convoy* on the slip road must start travelling *t* seconds earlier than the *convoy* on the main road. The start time lag $t_{startTimeLag}$ for all the junctions is calculated as,

$$t^{j}_{startTimeLag} = \left( \sum_{i=1}^{n} \left( \frac{d'_{speedChange}}{v} \right)_{i}^{mainRoad} - \sum_{i=1}^{n} \left( \frac{d'_{speedChange}}{v} \right)_{i}^{slipRoad} \right)_{j} \quad (25)$$

  where *n* = number of speed changes between the start location of the convoy and the respective junction $j$, $d'_{speedChange}$ = distance between two speed changes, starting from the depot or last holding location before arrival at junction *j* for respective *convoys, v* = velocity as per current speed limit for slip associated to junction $j$.

- The $t_{startTimeLag}$ is added to the start time of *convoy's* journey. This information could be identified beforehand and relayed prior to the start of journey, at different depots or holding locations around the region such that the vehicles travelling separately do depart at pre-determined time. Furthermore, by utilising connected infrastructure, the movement of different *convoys* could be monitored to ensure smooth passage of vehicles through the road network.

To calculate the $rP_{subsequent}$ location for the slip roads with travelling *convoy*, first calculate the time taken by preceding vehicles to reach individual junctions from the $rP_{primary}$ as,

$$t_{preced} = \left( \frac{d'_{junc} + \Delta L_{convoy}}{v^{mainRoad}_{preced}} \right) \quad (26)$$

where $\Delta L_{convoy}$ = currently merged *convoy* length for approaching junction, $v^{mainRoad}_{preced}$ = current velocity of *preceding* vehicles on main road.

Adding (23) to (26), the $rP_{subsequent}$ is calculated as,

$$rP_{subsequent} = \left( v^{slipRoad}_{preced} \times t_{preced} \right) + d^{j}_{\vec{a}} + \delta \quad (27)$$

where $v^{slipRoad}_{preced}$ = velocity of *preceding* vehicles on the slip.

The calculated $rP_{subsequent}$ location in (27) would be sufficient to generate an appropriate gap between *preceding*, *convoy* and *following* vehicle groups on the slip roads to merge with their respective counterparts on the main road.

#### 4.4.2.4. Multiple Junctions with Multiple Speeds and Convoys

For scenarios with single or multiple convoys on the roads with multiple mandatory speeds limits and multiple junctions, $rP_{primary}$ will be calculated as (11), additional $rP_{subsequent}$ locations for all road sections as (27), and additional mandatory speed changes for individual road sections as (14).

### 4.4.3. Reset Geo-Reference Locations

Once the geo-referenced locations are identified to reduce the speed of the vehicles to generate appropriate gaps between the *CA-DGVs* and its preceding and following vehicles, it is also imperative to appropriately reset the modified speed limits at $rP_{primary}$ and $rP_{subsequent}$ locations to original limits in order to optimise the traffic flows. In order to calculate the $rP_{reset}$, first determine the difference between the positioning calculated for *DGVs* and *following* vehicles (for $b \in B$), in (11), (14) and (19) for $rP_{primary}$ and $rP_{subsequent}$.

$$posDifference = \left|(d_{DGV} - d_{follow})\right| \tag{28}$$

Using (28) calculate the distance between the $rP$ position calculated for following vehicles and $posDifference$ as,

$$d_{posDifference} = d_{follow} - posDifference \tag{29}$$

Now calculate the time *t* taken by *following* vehicles to reach the tunnel, or $rP_{subsequent}$ as,

$$t_{follow}^{d_{follow}} = \frac{d_{follow}}{v_{follow}} \tag{30}$$

$$t_{follow}^{d_{posDifference}} = \frac{d_{posDifference}}{v_{follow}} \tag{31}$$

$$t_{follow}^{extraDuration} = \left|\left(t_{follow}^{d_{follow}} - t_{follow}^{d_{posDifference}}\right)\right| \tag{32}$$

Using (32), calculate the $rP_{reset}$ as,

$$rP_{reset} = \left(t_{follow}^{extraDuration} \times v_{follow}\right) + posDifference \tag{33}$$

The $rP_{reset}$ must be calculated for $rP_{primary}$ and all $rP_{subsequent}$ location, depending on the road layout, and must be positioned on the *MainRoad*, positioned upstream from tunnel's entrance. The relevant speed limits would then be reset to original speeds, including change made on the slip roads.

## 4.5. Simulation Setup

To demonstrate the accuracy of the mathematical model, the PTV Vissim simulations are performed for six road layout scenarios where the convoy of *CA-DGVs* are simulated in mixed traffic *Cars* and *HGVs* as conventional vehicles, approaching a 200 meters long tunnel. A short tunnel of is used to demonstrate the effectiveness of the model in generating gaps. This is because the model is independent of the tunnel's length and with a 200 meters long tunnel the $rP$ points on main or slip road would be ~2,500m which would help accurately analyse the generation of gaps and traffic flow conditions during the simulations. The simulations are aimed at proving two hypotheses in two phases.

*Phase I* tests the hypothesis that $rP$ geo-locations, as calculated by the mathematical model, are appropriately positioned for dynamic generation of desired gaps by modulating traffic speeds and the *convoy* is able to travel via a tunnel in isolation. The evaluations are visually analysed as stepwise flow of traffic simulation for each of the six road layout scenarios mentioned in Section 4.4. In PTV Vissim, the conventional vehicles are defined using Wiedemann 99 car following behaviour and connected vehicles are defined as per the CoEXist project.

*Phase* II tests the hypothesis and analyses the effectiveness of dynamic gaps and speed variations in improving overall traffic flow. The evaluations are measured on basis of Average Traffic Density (ATD), AVTT and AMQL, which are captured at five seconds interval during simulations. For graphs the resolution of capture is increased to 30 seconds. For *Baseline* results, a subset of Dartford Crossing tunnel, only involving escorting procedures on main road using conventional vehicles (*Cars*, *HVG* and *Declared DGVs*) controlled via traffic signals is simulated. For further analysis, for each of the six road layout scenarios, two sub-scenarios are identified as:

- Simulation of mixed traffic (*Cars, HGVs* and *CA-DGVs*) and achieving dynamic gap generation, labelled as *MixedTraffic*. This study assumes the dynamic speed updates for conventional vehicles via VMS and enforced using speed cameras, and for connected convoy via C-ITS communications and enforced using in-Vehicle SPeeD limits (VSPD) [142] and similar services.
- Simulation of all vehicles running as *CA-Cars*, *CA-HGVs* and *CA-DGVs*, labelled as *CAV*.

For this setup, the simulation model simulates the real-world AAHT and traffic compositions for *Cars*, *HGVs* and *DGVs* as analysed using Dartford Crossing tunnel data for which the appropriate permission from Highways England is obtained. The data is yearlong between March 2018 and February 2018. In addition to AAHT and composition, the waiting times for inspection, parking and escorting of *DGVs* are also considered for travel time analysis. Furthermore the PTV Vissim's platooning functionality [163] is enabled for the *convoy* vehicle category with following parameters:

- Maximum number of *CA-DGVs* = 6
- Maximum desired speed = 50mph
- Maximum distance for catching up to a platoon = 250m
- Gap time = 0.20s
- Minimum clearance = 1.50m

The calculation, implementation and dynamic speed modulations as identified by mathematical model are performed using PTV Vissim's COM interface [164] via Python scripting language. The $rP$ locations are calculated and placed at a measured distance from the tunnel entrance using *Detectors* (Vissim's object) which are triggered when *CA-DGVs* category vehicle a.k.a. the *convoy* passes over it. The simulation is configured to run for 350s which is a suitable duration for vehicles to journey ~2,500m distance. The main road link is a 4-lane road and slip roads are 2-lanes (wherever applicable). The *CA-DGVs* vehicles are dynamically added to the network after 90s of simulation run, to ensure road(s) are sufficiently saturated of vehicles. The number of *convoy* vehicles added on individual roads is based up on the road layout scenario. To ensure the simulation results are not due to *chance*, each simulation scenario run is configured for 10 random runs using a random seed, defined using general simulation parameters '*Random Seed'* generator [165] in the software. The common list of parameters and their settings for difference scenarios are listed in Table 28.

Table 28 Common Simulation Settings for seven traffic simulation scenarios

| **Parameters** | **Conventional Vehicles** | | | **Connected Vehicles (CAV)** | | |
|---|---|---|---|---|---|---|
| | ***Cars*** | ***HGVs*** | ***DGVs*** | ***CA-Cars*** | ***CA-HGVs*** | ***CA-DGVs*** |
| **AAHT** | 3000/hr (Main road) and 2000/hr (Slip roads) | | | | | |
| **Traffic composition** | 82% | 18% | 5/hr | 82% | 18% | 4 (single lane)<br>6 (multi lanes) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Average Wait Time** | N/A | N/A | 33min | N/A | | |
| **Platoon count** | N/A | | | N/A | N/A | 4 (single lane) 6 (multi lanes) |
| $d_{safe}$ | N/A | | | 50m | | |
| $d_{stop}$ | ~21m | | | ~15m | ~15m | 6m |
| **Vehicle Length** | 5.21-11.6m | >11.6 m | 8.85m | 5.2-11.6m | >11.6m | 8.85m |
| **Average Desired Acceleration** | 1.01m/s$^2$ | 1.33m/s$^2$ | 1.33m/s$^2$ | 1.01m/s$^2$ | 1.24m/s$^2$ | 1.24m/s$^2$ |
| **Average Desired Deceleration** | -2.75m/s$^2$ | -1.25m/s$^2$ | -1.25m/s$^2$ | -2.75m/s$^2$ | -1.25m/s$^2$ | -1.25m/s$^2$ |
| **Latency (δ)** | N/A | | | 100ms | | |
| **Constant (ε)** | N/A | | | 10m | | |
| **Speed fluctuations** | $\pm$10% | | | $\pm$1mph | | |

The detailed setup on per scenario basis is explained in subsequent sections. Note that all the distances measured and calculated were rounded to nearest number and were in meters.

### 4.5.1. Baseline Layout based on Dartford Crossing with Traffic Signals

Figure 22 shows the baseline simulation model simulating a subset of DGVs monitoring procedure using traffic signals at Dartford Crossing tunnel.

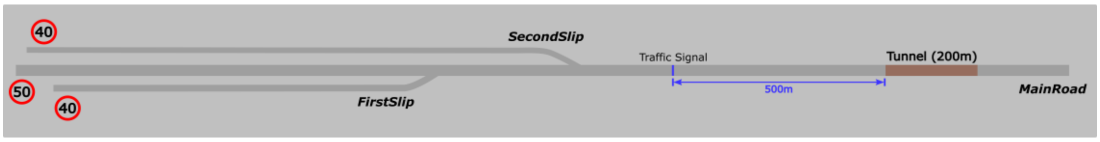


*Figure 22 Baseline road layout with traffic signal to control the flow of conventional DGVs, as observed at Dartford Crossing tunnel*

For this scenario the *Cars*, *HGVs* and *DGVs* vehicles are simulated as conventional vehicles, mimicking the real-world traffic flow with AAHT of 3000 vehicles. During the simulation the traffic is stopped at a traffic signal, placed at a distance of 500 meters from tunnel's entrance, when DGVs vehicles are detected by the PTV Vissim's *'Detector'* component. The traffic is then hold for an average of 180 seconds, as determined using the Dartford Crossing data. The impact of DGVs crossing and closures at the tunnel are captures using indicators*: Travel Time*, *Queue Length* and *Traffic Density*.

### 4.5.2. Single Road Layout with Single Speed Limit

Figure 23 shows the road layout of length 2500 meters with one mandatory speed limit of 50mph.


*Figure 23 Simulation for single road layout with single mandatory speed limit.*

Four *CA-DGVs* vehicles as a convoy are simulated on the *MainRoad*. To ensure the isolated travel of *CA-DGVs* via the tunnel, the $rP_{primary}$ is positioned at a distance of 1329 meters upstream from the tunnel's entrance and $rP_{reset}$ is positioned at 523 meters from the tunnel's entrance. The speeds of *CA-Cars* and *CA-HGVs* vehicles are reduced when the last vehicle in the convoy of *CA-DGVs* vehicles crosses $rP_{primary}$ geo-location, based on their positioning with respect to the convoy i.e. *preceding* (and alongside) or *following* it. At the $rP_{primary}$ the speed of *preceding* vehicles was retained at 50mph but for the *CA-DGVs* speed limit is reduced to 40mph and for *following* vehicles to 30mph.

### 4.5.3. Single Road Layout with Multiple Speed Limits

Figure 24 shows the road layout of length 2700 meters (including the 200 meters long tunnel) with three mandatory speed limits of 70mph, 60mph and 50mph.

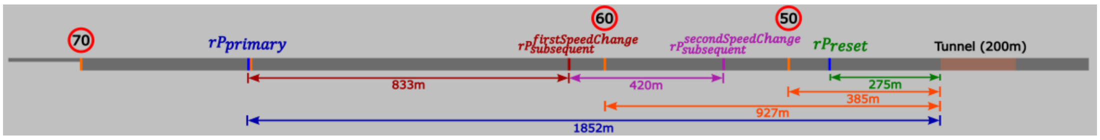


*Figure 24 Simulation for single lane but multiple speed limits road layout scenario.*

Four *CA-DGVs* vehicles as a convoy are simulated on the *MainRoad*. The $rP_{primary}$ is geo-positioned at a distance of 1852 meters upstream from the tunnel's entrance. When the last vehicle of the *CA-DGVs* convoy crosses this location, the speeds of *preceding*, *convoy* and *following* vehicles are adjusted as 70mph, 60mph and 50mph respectively. To adjust for second mandatory speed limit of 60mph located at 927 meters from the tunnel's entrance, the $rP_{subsequent}^{firstSpeedChange}$ is positioned upstream at 833 meters as measured downstream from $rP_{primary}$. The speeds of *preceding*, *convoy* and *following* vehicles are adjusted as 60mph, 50mph and 40mph respectively. The third mandatory speed limit of 50mph is located at 420 meters upstream from the tunnel's entrance and the $rP_{subsequent}^{secondSpeedChange}$ is positioned at 385 meters downstream from $rP_{subsequent}^{firstSpeedChange}$. The speeds of *preceding*, *convoy* and *following* vehicles are adjusted as 50mph, 40mph and 30mph respectively. The $rP_{reset}$ is positioned after the third mandatory speed change at a distance of 275 meters from the tunnel's entrance.

### 4.5.4. Multiple Roads with Single Speed Limit and a Convoy

Figure 25 shows the simulation layout with three separate roads named as *MainRoad* (2577 meters), *FirstSlip* (355 meters) and *SecondSlip* (1398 meters).

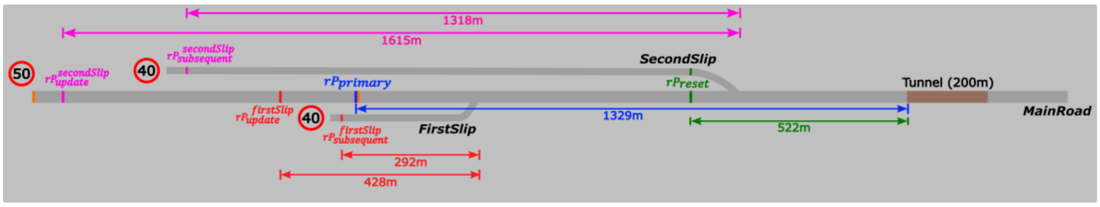


*Figure 25 Simulation of single CA-DGVs convoy on layout with multiple roads with single speed limits.*

The *FirstSlip* merges with the *MainRoad* at a distance of 1069 meters and *SecondSlip* at a distance of 428 meters as calculated from the tunnel's entrance. The *MainRoad* has single mandatory speed limit of 50mph and the two slip roads have single mandatory speed limit of 40mph, respectively. Four *CA-DGVs* vehicles as a convoy are simulated on the *MainRoad*. The $rP_{primary}$ is positioned upstream at 1329 meters from the tunnel's entrance on the *MainRoad*. The $rP_{subsequent}^{firstSlip}$ is positioned upstream at 292 meters from the junction of *FirstSlip* with *MainRoad*. The $rP_{subsequent}^{secondSlip}$ is positioned upstream at 1318 meters from the *SecondSlip* junction with *MainRoad*. The $rP_{update}^{firstSlip}$ is positioned on *MainRoad* at a distance of 428 meters from *FirstSlip* junction upstream. The $rP_{update}^{secondSlip}$ is positioned on *MainRoad* at 1615 meters from *SecondSlip* junction upstream. Finally, $rP_{reset}$ is positioned at 522 meters upstream from the tunnel's entrance on the *MainRoad*. As four *CV-DGVs* vehicles are traveling on the *MainRoad*, at $rP_{update}^{firstSlip}$, when the last vehicle of the *CA-DGVs* convoy is passed, at $rP_{subsequent}^{firstSlip}$ the speeds are reduced to 30mph such that vehicles past this point travelling at 40mph are joined with *preceding* vehicle group on the *MainRoad* and the with reduced speed limit are joined with *following* vehicle group on the *MainRoad* with a suitable gap to accommodate *CV-DGVs* convoy. Similarly, when the last vehicle in the convoy crossed the $rP_{update}^{secondSlip}$, the speed limit is reduced to 30mph at $rP_{subsequent}^{secondSlip}$ geo-location.

### 4.5.5. Multiple Roads and Convoys with Single Speed Limit

Figure 26 shows the layout with multiple road sections named as *MainRoad* (2278 meters), *FirstSlip* (486 meters) and *SecondSlip* (1292 meters).

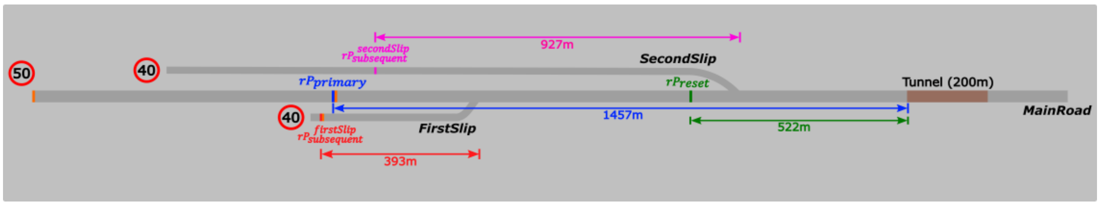


*Figure 26 Simulation of Multiple CA-DGVs convoys on layout with multiple roads and single speed limits.*

The *FirstSlip* merges with the *MainRoad* at a distance of 1069 meters and *SecondSlip* at a distance of 428 meters as calculated from the tunnel's entrance. The *MainRoad* has single mandatory speed limit of 50mph and the two slip roads have single mandatory speed limit of 40mph, respectively. As in this scenario the study tests the merging of *CV-DGVs* vehicles from separate road to travel as one convoy via the tunnel, and to comply with maximum convoy limit of 6 vehicles, on each of the three roads two *CA-DGVs* vehicles are added. They as per time lag calculated as, $t^{mainRoad}_{startTimeLag}$= 900 simulation steps, $t^{firstSlip}_{startTimeLag}$= 1026 simulation steps (time lag of 12.5 seconds) and $t^{secondSlip}_{startTimeLag}$= 854 simulation steps (time lag of -4.6 seconds). The $rP_{primary}$ is positioned upstream at 1457 meters from the tunnel's entrance on the *MainRoad*. The $rP^{firstSlip}_{subsequent}$ is positioned upstream at 393 meters from the junction of *FirstSlip* with *MainRoad*. The $rP^{secondSlip}_{subsequent}$ is positioned upstream at 927 meters from the *SecondSlip* junction with *MainRoad*.

### 4.5.6. Multiple Roads and Speed Limits with Single Convoy

Figure 27 shows the layout with multiple road sections named as *MainRoad* (3084 meters), *FirstSlip* (976 meters) and *SecondSlip* (1800 meters).

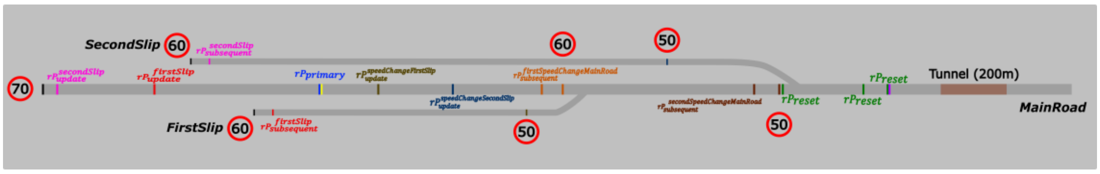


*Figure 27 Simulation of Single CA-DGVs convoy on layout with multiple roads and multiple speed limits.*

The *FirstSlip* merges with the *MainRoad* at a distance of 1069 meters and the *SecondSlip* at a distance of 427 meters as calculated from the tunnel's entrance. The *MainRoad* has three mandatory speed limits as 70mph, 60mph and 50mph. The 60mph mandatory speed change is at a distance of 1129 meters and the 50mph mandatory speed change is at a distance of 479 meters from the tunnel's entrance. The two slip roads have two mandatory speed limits as 60mph and 50mph, respectively. For the *FirstSlip* the 50mph mandatory speed change is at a distance of 167 meters from its junction to *MainRoad*. The 50mph mandatory speed change for the *SecondSlip* is at 385 meters from its junction to the *MainRoad*. The $rP_{primary}$ is positioned upstream at 1852 meters from the tunnel's entrance on the *MainRoad*. The $rP_{subsequent}^{firstSlip}$ is positioned upstream at 918 meters from the junction of *FirstSlip* with *MainRoad*. The $rP_{subsequent}^{secondSlip}$ is positioned upstream at 1743 meters from the *SecondSlip* junction with *MainRoad*. The $rP_{update}^{firstSlip}$ is positioned on *MainRoad* at a distance of 1278 meters from *FirstSlip* junction upstream. The $rP_{update}^{secondSlip}$ is positioned on *MainRoad* at 2206 meters from *SecondSlip* junction upstream. To adjust to upcoming mandatory speed changes on *MainRoad* and two slip roads, the additional geo-referenced locations are determined on the *MainRoad*. To adjust for the first speed change on the *MainRoad* (70mph to 60mph), the $rP_{subsequent}^{firstSpeedChangeMainRoad}$ is positioned at 661 meters downstream from $rP_{primary}$, and for the second speed change on the *MainRoad* (60 mph to 50 mph), the $rP_{subsequent}^{secondSpeedChangeMainRoad}$ is positioned at 635 meters downstream from $rP_{subsequent}^{firstSpeedChangeMainRoad}$. To adjust for the first speed change on the *FirstSlip* (60 mph to 50 mph), the $rP_{subsequent}^{firstSpeedChangeFirstSlip}$ is positioned at 672 meters downstream from $rP_{update}^{firstSlip}$ on the *MainRoad*. To adjust for the first sped change on the *SecondSlip* (60 mph to 50 mph), the $rP_{subsequent}^{firstSpeedChangeSecondSlip}$ is positioned at 1181 meters downstream from $rP_{update}^{secondSlip}$ on the *MainRoad*. Finally, three $rP_{reset}$ positions are calculated to reset changes at $rP_{primary}$ and $rP_{subsequent}$ locations and are positioned at 475 meters, 238 meters and 207 meters respectively from the tunnel's entrance.

## 4.5.7. Multiple Roads Layout, Speed Limits and Convoys

Figure 28 shows the layout with multiple road sections named as *MainRoad* (2278 meters), *FirstSlip* (682 meters) and *SecondSlip* (1398 meters).

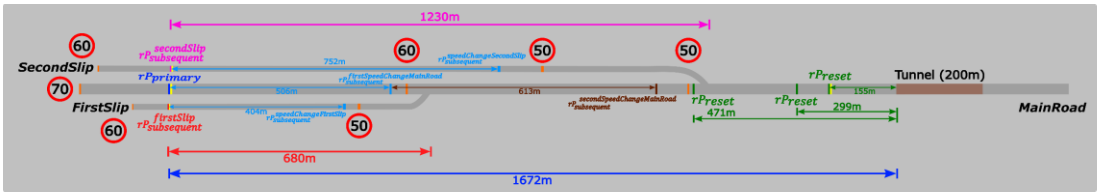

*Figure 28 Simulation of multiple CA-DGVs convoys on layout with multiple roads and multiple speeds.*

The *FirstSlip* merges with the *MainRoad* at a distance of 1069 meters and *SecondSlip* at a distance of 428 meters as calculated from the tunnel's entrance. The *MainRoad* has three mandatory speed limits as 70mph, 60mph and 50mph. The 60mph mandatory speed change is at a distance of 1129 meters and the 50mph mandatory speed change is at a distance of

479 meters from the tunnel's entrance. The two slip roads have two mandatory speed limits as 60mph and 50mph, respectively. For the *FirstSlip* the 50mph mandatory speed change is at a distance of 165 meters from its junction to *MainRoad*. The 50mph mandatory speed change for the *SecondSlip* is at a distance of 372 meters from its junction to the *MainRoad*. Two *CA-DGVs* vehicles as a convoy are simulated on each of the road sections at different time interval calculated as, $t_{startTimeLag}^{mainRoad}$= 900 simulation steps, $t_{startTimeLag}^{firstSlip}$= 922 simulation steps (time lag of 2.2 seconds) and $t_{startTimeLag}^{secondSlip}$= 825 simulation steps (time lag of -7.5 seconds). The $rP_{primary}$ is positioned upstream at 1672 meters from the tunnel's entrance on the *MainRoad*. The $rP_{subsequent}^{firstSlip}$ is positioned upstream at 680 meters from the junction of *FirstSlip* with *MainRoad*. The $rP_{subsequent}^{secondSlip}$ is positioned upstream at 1230 meters from the *SecondSlip* junction with *MainRoad*. Adjusting for speed changes on the *MainRoad,* for 60mph mandatory speed limit the $rP_{subsequent}^{firstSpeedChangeMainRoad}$ is positioned at 506 meters downstream from $rP_{primary}$. The speeds of *preceding*, *convoy* and *following* vehicles are adjusted as 60mph, 50mph and 40mph, respectively. For 50mph mandatory speed limit the $rP_{subsequent}^{secondSpeedChangeMainRoad}$ is positioned at 613 meters downstream from $rP_{subsequent}^{firstSpeedChangeMainRoad}$. The speeds of *preceding*, *convoy* and *following* vehicles are adjusted as 50mph, 40mph and 30mph, respectively. Adjusting for speed changes on the *FirstSlip,* for 50mph mandatory speed limit the $rP_{subsequent}^{speedChangeFirstSlip}$ is positioned at 404 meters downstream from $rP_{subsequent}^{firstSlip}$. The speeds of *preceding*, *convoy* and *following* vehicles are adjusted as 50mph, 40mph and 30mph, respectively. Adjusting for speed changes on the *SecondSlip,* for 50mph mandatory speed limit the $rP_{subsequent}^{speedChangeSecondSlip}$ is positioned at 752 meters downstream from $rP_{subsequent}^{secondSlip}$. The speeds of *preceding*, *convoy* and *following* vehicles are adjusted as 50mph, 40mph and 30mph, respectively. The $rP_{reset}$ is calculated for *MainRoad* speed changes and are positioned from the tunnel's entrance at 471 meters for speed adjustments at $rP_{primary}$, 229 meters for $rP_{subsequent}^{firstSlip}$ and 155 meters for $rP_{subsequent}^{secondSlip}$.

## 4.6. Results

The results are detailed in two phases. The first phase aims at verifying the mathematical model's approach in generating dynamic gaps using PTV Vissim traffic simulation, by visual analysis. In second phase, the study analysis the impact of dynamic modulation of speed and vehicular gaps between the *preceding, convoy* and *following* vehicle groups with regards to travel time, traffic flow and queue formations.

### 4.6.1. Phase I – Visual Inspection Analysis

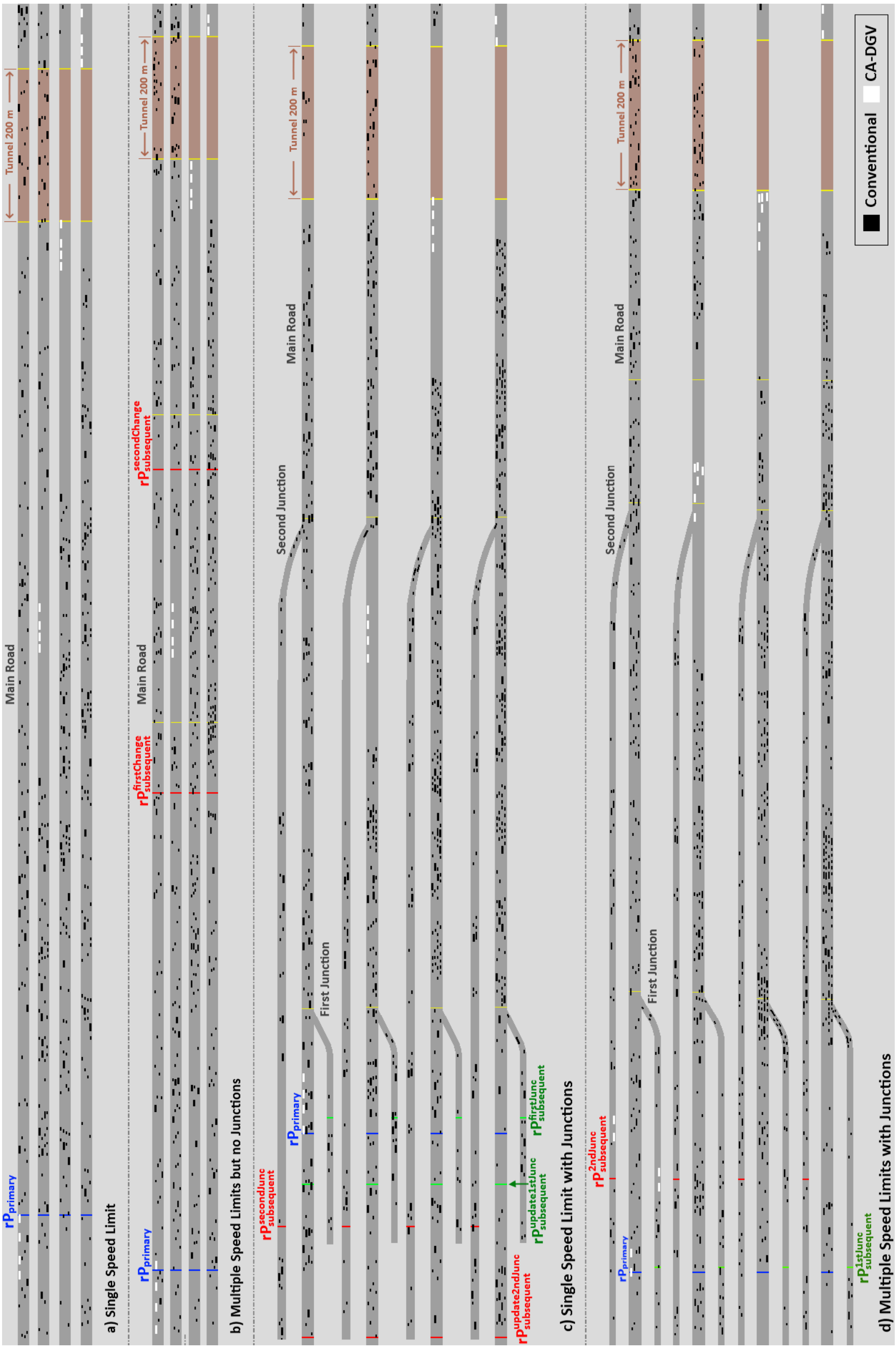


*Figure 29 Dynamic gap generation in simulated stepwise sequence for four road layouts.*

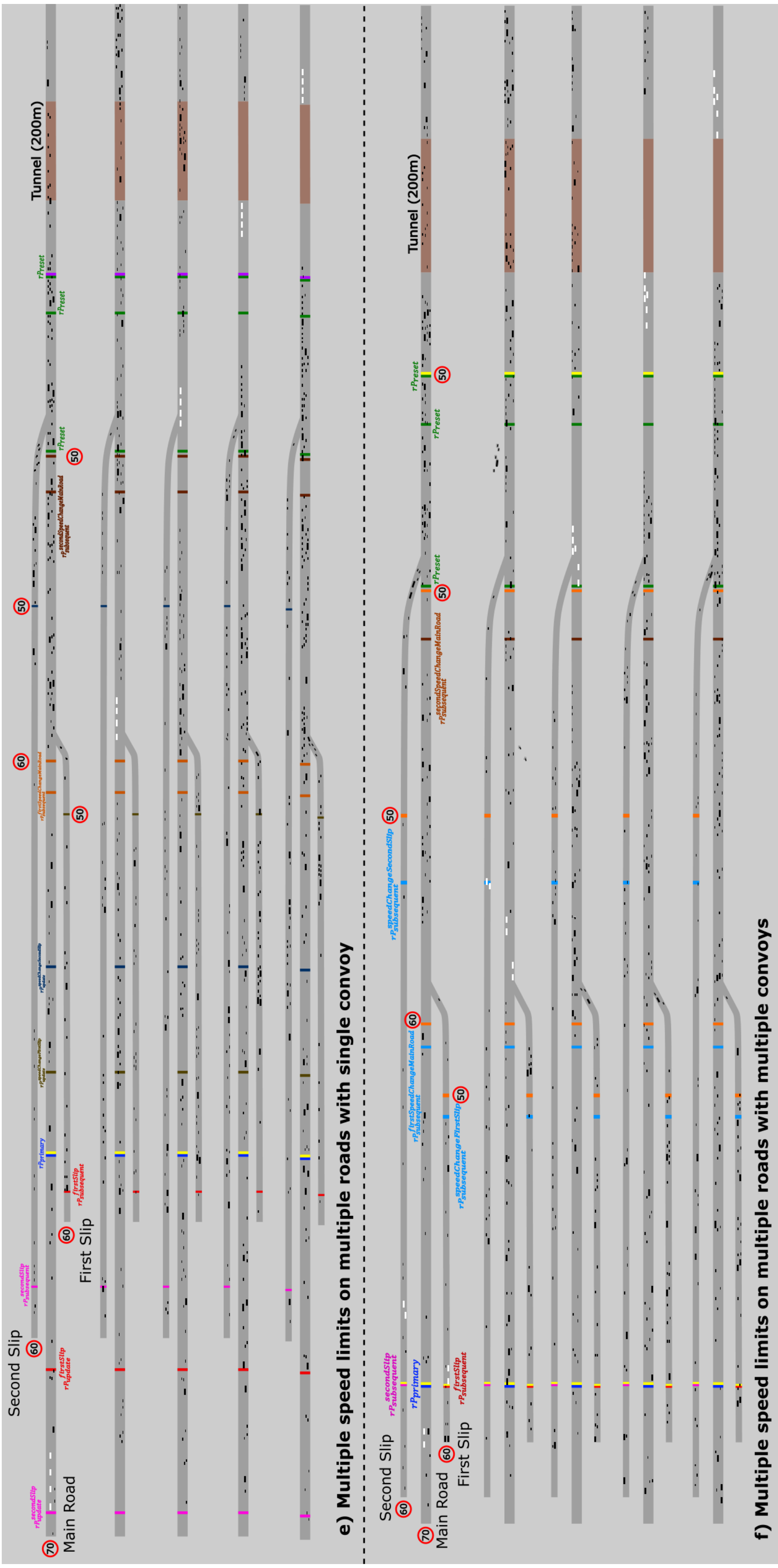


*Figure 30 Dynamic gap generation in simulated stepwise sequence for two road layouts.*

The results illustrate dynamic gap generation between *preceding*, *convoy* and *following* vehicles and isolated travel of *convoy* via a tunnel as stepwise flow sequences shown in Figure 29 (a-d) and *Figure 30* (e-f). From the sequences for all the simulated scenarios, it could be concluded that the geo-reference locations on the main road ($rP_{primary}$) and on the slip roads ($rP_{subsequent}$) were appropriately calculated and placed. The simulation scenario sequences show that by retaining the speed of *preceding* vehicles and adjusting the speeds of the *convoy* and *following* vehicles at $rP$ locations, the desired gaps $g$ were successfully generated, leading to isolated travel of *DGVs* via the road tunnel. To ensure the adjusted speed limits were reset following the passage of the *convoy*, in the simulation the speeds at $rP$ locations were reset periodically to ensure *following* vehicles were at ~50m ($d_{safe}$) distance from the tunnel, once the *convoy* has exited the tunnel, as observed in the Figure 29 and *Figure 30*. From the simulation it was observed that once the speed limits were reset, the following vehicles now travelling at faster speeds were blocked by traffic in front and does not affect the generated gaps.

## 4.6.2. Phase II

In this section the dynamic gap generation using the mathematical model is compared for traffic performance indicators: ATD, AVTT and AMQL for six road layout scenarios. The simulation runs were 480s and average of 10 simulation runs per scenario was performed using random seeds [165] to ensure no two simulations are exactly same as in real-world.

### 4.6.2.1. Single Road Layout with Single Speed Limit

Figure 31 and Figure 32 shows the comparison of Average Traffic Density (ATD) and AVTT, respectively, between three simulation categories *Baseline*, *Mixed Traffic* and *CAV* for the layout with single road with single mandatory speed of 50 mph. The Shaprio Wilk's test was conducted for the measurements to access the normality along with boxplots to identify outliers and homogeneity of variance using Leven's test. The details of the analysis are reported on the respective graphs.

#### 4.6.2.1.1. ATD Analysis

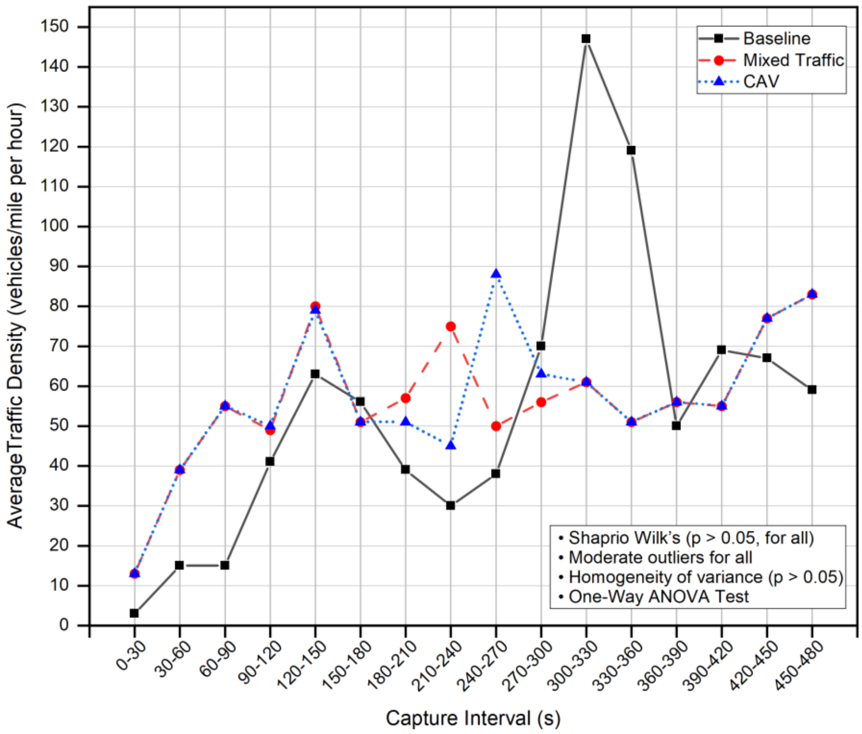


*Figure 31 Average Traffic Density analysis for single lane with single speed limit scenario.*

A One-Way ANOVA test was conducted. The ATD increased from the *Baseline* ($N$ = 96, $M$ = 59.17, $SD$ = 34.75), to *CAV* ($N$ = 96, $M$ = 58.00, $SD$ = 19.58) to *Mixed Traffic* ($N$ = 96, $M$ = 57.48, $SD$ = 17.80) scenarios, in that order, but ATD between these categories was not statistically significant different, $F(2, 180.76) = 0.091$, $p = 0.913$.

As observed, the ATD between three simulation categories did not differ when comparing means. But by analysing the graphs, a clear shift in the density pattern could be noted. It was calculated that initially for *Baseline* scenario, the ATD was ~56% lower than the ATD of *Mixed Traffic* and *CAV* scenarios. Between *Mixed Traffic* and *CAV* simulation the ATD remained similar throughout the simulation but ATD for *CAV* was ~17% higher than *Mixed Traffic*, during the gap formation, which could be because of more vehicles being accommodated due to smaller headway between vehicles in all *CAV* scenario. Another important point to note is that for *Baseline* category, it took ~150 seconds to ease congestion following the tunnel closure due to escort of DGVs, in comparison to *Mixed Traffic* in ~120 seconds (20% improvement) and *CAV* in ~90 seconds (40% improvement) using dynamic gap generation.

## 4.6.2.1.2. AVTT Analysis

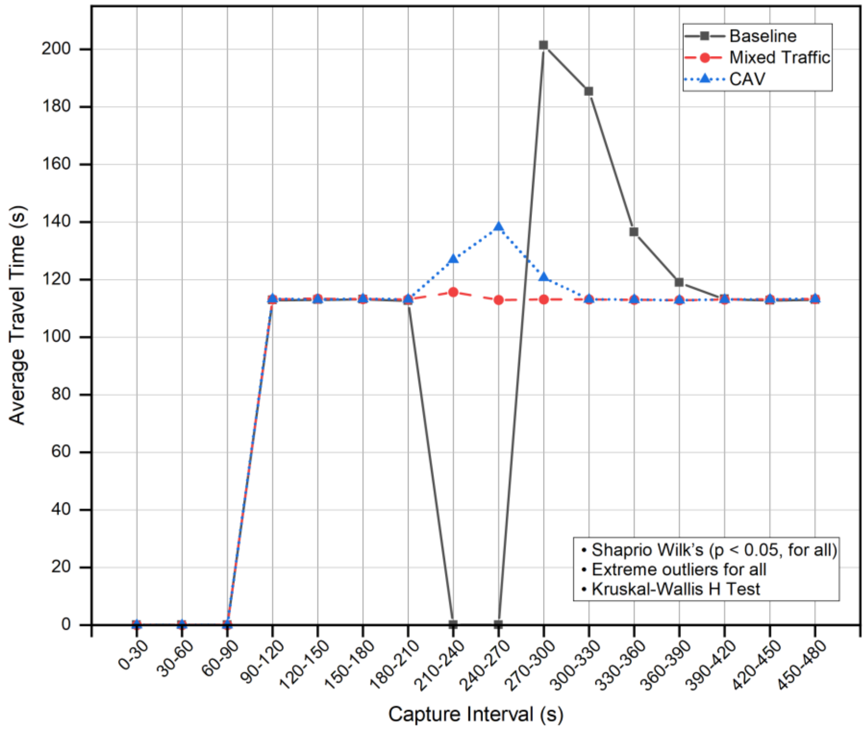


*Figure 32 AVTT analysis for single lane with single speed limit scenario.*

Figure 32, a Kruskal-Wallis H test [166] was conducted to determine if there were differences in AVTT between categories. Distributions of AVTT scores were not similar for all categories, as assessed by visual inspection of a boxplot. AVTT increased from the *Baseline* (*N* = 96, *Mean Rank (MR)* = 130.65), *Mixed Traffic* (*N* = 96, *MR* = 145.52) to *CAV* (*N* = 96, *MR* = 157.33), but the ATD differences were not statistically significant, $\chi^2(2) = 5.645\ \ p = 0.059$.

Although, the AVTT between the categories were observed to be statistically similar, a contrast could be seen in the Figure 32 between categories. The maximum AVTT observed for the *Baseline* was measured at ~201 seconds, in comparison to ~116 seconds for *Mixed Traffic* and ~139 for *CAV* scenarios, i.e. a decrease of ~43% and ~31% respectively, when the traffic was stopped for DGVs isolated travel. Also, the AVTT between the *Mixed Traffic* and *CAV* was mostly similar, except for the duration when dynamic gap generation was in progress, during which the AVTT increased by ~16% for *CAV* scenario in comparison to *Mixed Traffic* scenario. The graphs also shows the approximate uniform travel times for *Mixed Traffic* and *CAV* simulation scenario, in comparison to *Baseline* scenario.

## 4.6.2.1.3. AMQL Analysis

The AMQL on the *MainRoad* was observed to be zero for *Mixed Traffic* and *CAV* simulation categories. For *Baseline* the AMQL was observed at ~114 meters during the tunnel closure.

#### 4.6.2.2. Single Road Layout with Multiple Speed Limits

Figure 33 and Figure 34 shows the comparison of ATD and AVTT, respectively, between three simulation categories *Baseline*, *Mixed Traffic* and *CAV* for the scenario with single road but having multiple speed changes, 70mph to 60mph to 50mph, prior to tunnel's entrance. The Shaprio Wilk's test was conducted to access the normality along with boxplots to identify outliers and homogeneity of variance using Leven's test.

##### 4.6.2.2.1. ATD Analysis

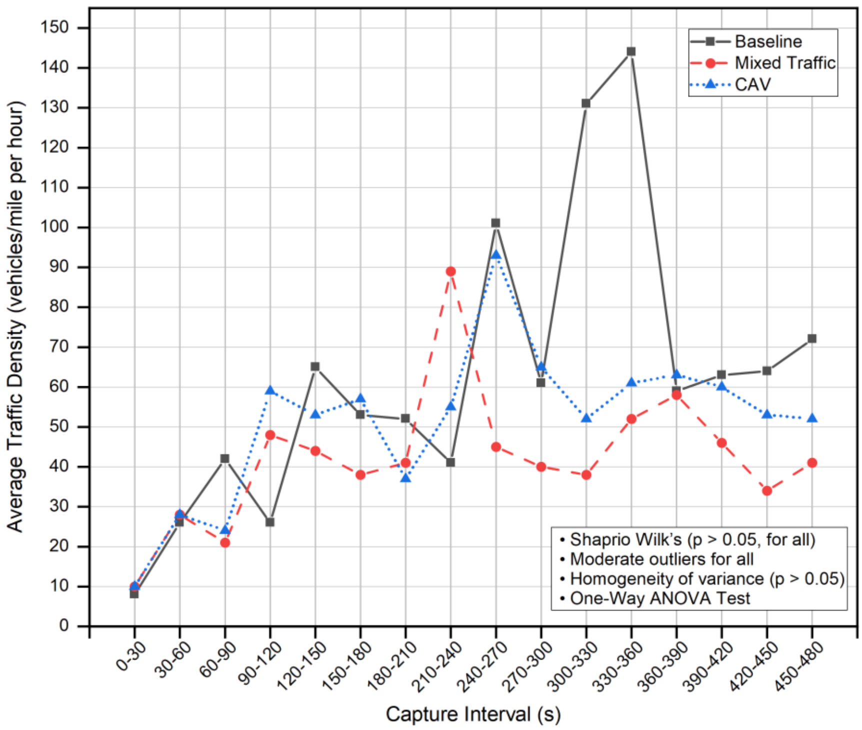


*Figure 33 Average Traffic Density analysis for single lane with multiple speed limits scenario.*

Figure 33, a One-Way ANOVA was conducted and the ATD increased from the *Mixed Traffic* ($N$ = 96, $M$ = 42.58, $SD$ = 17.25), to *CAV* ($N$ = 96, $M$ = 51.83, $SD$ = 19.28) to *Baseline* ($N$ = 96, $M$ = 63.41, $SD$ = 36.09) scenarios, in that order, but the ATD between these categories was not statistically significant different, $F(2, 45) = 2.65$, $p = 0.081$.

By observing the Figure 33, a difference in ATD were observed between the three categories. It was calculated that by comparison ATD increased by ~60% between the *Baseline* and *Mixed Traffic* categories, and by ~55% in between *Baseline* and *CAV* categories. Between the *Mixed Traffic* and *CAV*, the ATD increased by ~3%. Here again, for *Baseline* category it took ~150 seconds to ease congestion following the tunnel closure due to escort of DGVs, in comparison to *Mixed Traffic* in ~120 seconds (20% improvement) and *CAV* in ~90 seconds (40% improvement) using dynamic gap generation approach. Overall, for the *Mixed Traffic* category the ATD performed better and was observed to be the lowest between the simulations.

#### 4.6.2.2.2. AVTT Analysis

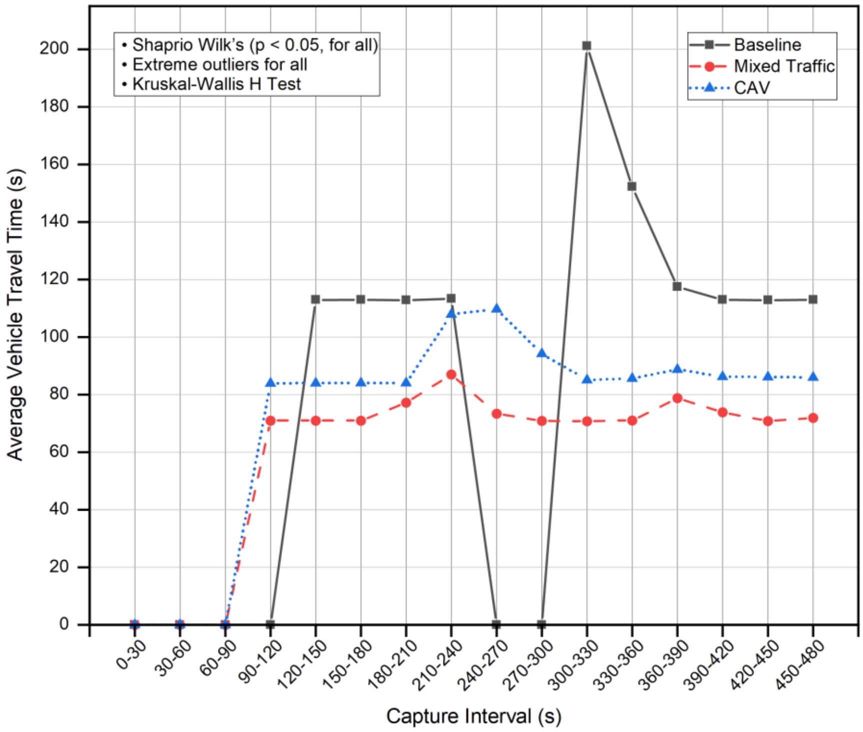


*Figure 34 AVTT analysis for single lane with multiple speed limits scenario.*

Figure 34, a Kruskal-Wallis H test was conducted to determine the differences in AMQL between the categories. Distributions of AMQL scores were similar for all groups, as assessed by visual inspection of a boxplot. Median AVTT were statistically significantly different between the categories, $\chi^2(2) = 29.05,\ p < 0.005$.

Subsequently, pairwise comparisons were performed using Dunn's (1964) procedure with a Bonferroni correction for multiple comparisons. Adjusted *p*-values are presented. This post hoc analysis revealed statistically significant differences in AVTT between all three category combinations, *Baseline* (*N* = 96, *Mdn* = 112.90) and *Mixed Traffic* (*N* = 96, *Mdn* = 71.0) (*p* < 0.005), *Baseline* and *CAV* (*N* = 96, *Mdn* = 86.00) (*p* = 0.018) and *Mixed Traffic* and *CAV* (*p* = 0.015).

By observing the graph, it could be noted that for *Baseline* the maximum AVTT was measured at ~201 seconds, in comparison to ~110 seconds for *CAV* and 87 seconds for *Mixed Traffic* scenarios. That is an increase of ~131% and ~84% in *Baseline* AVTT when compared to *Mixed Traffic* and *CAV* scenarios, respectively. Also, for the most efficient performing *Mixed Traffic* scenario, the AVTT was ~20% lower than that of *CAV* scenario.

### 4.6.2.2.3. AMQL Analysis

The AMQL on the *MainRoad* the single road with multiple mandatory speed layout was observed to be zero for *Mixed Traffic* and *CAV* in comparison to *Baseline* where AMQL was observed to be ~98 meters, during the tunnel closure.

## 4.6.2.3. Multiple Roads with Single Speed Limit and a Convoy

Figure 35 to Figure 42 show the ATD, AVTT and AMQL analysis for multiple road layout with single speed limit involving *MainRoad*, *FirstSlip* and *SecondSlip*, respectively, to determine if the measurements on these three road sections were statistically significantly different between *Baseline*, *Mixed Traffic* and *CAV* categories. The Shaprio Wilk's test was conducted for normality, along with boxplot analysis for outliers and homogeneity of variance was analysed using Leven's test.

### 4.6.2.3.1. ATD Analysis

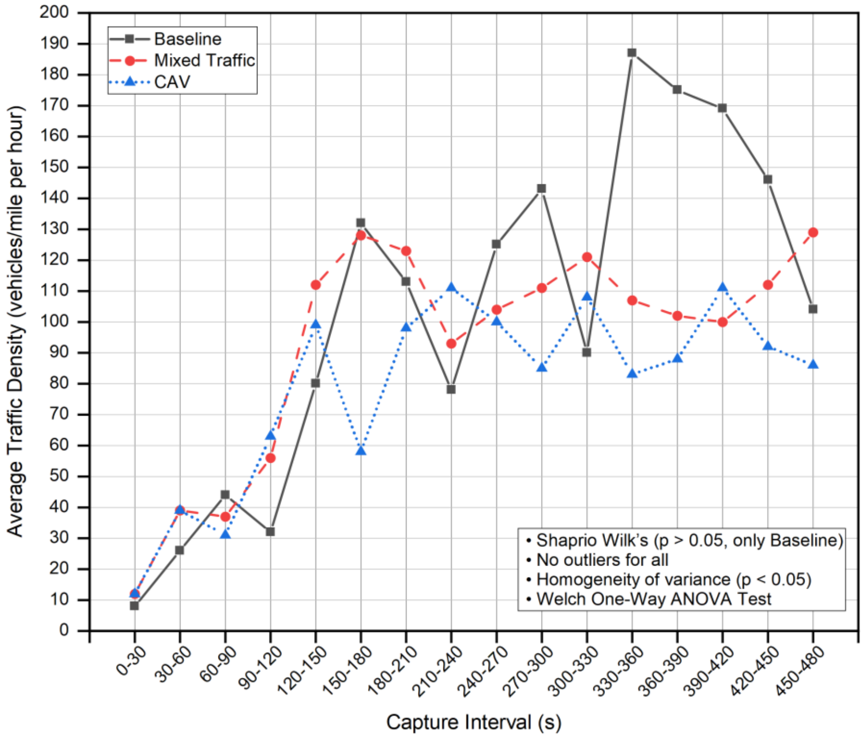


*Figure 35 ATD on MainRoad for multi roads with single speed limit and single convoy.*

Figure 35, the Welch One-Way ANOVA showed that ATD between these categories were statistically significantly similar, Welch's $F(2, 28.59) = 1.40$, $p = 0.261$ and it decreased from the *Baseline* ($N = 96$, $M = 103.68$, $SD = 55.83$), to *Mixed Traffic* ($N = 96$, $M = 93.50$, $SD = 36.22$) to *CAV* ($N = 96$, $M = 79.62$, $SD = 29.97$) category, in that order.

The ATD decreased by ~11% between *Baseline* and *Mixed Traffic* category and by ~23% *Baseline* and *CAV*. Between the *Mixed Traffic* and *CAV* categories the ATD decreased by ~14% highlighting that *CAV* category performed better overall.

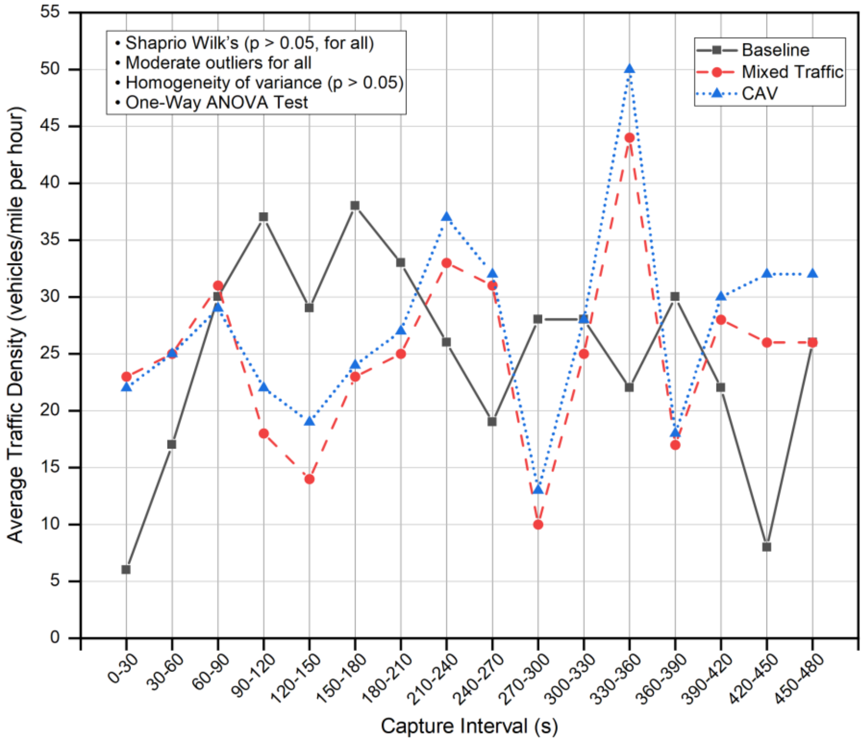


*Figure 36 ATD on FirstSlip for multi roads with single speed limit and single convoy.*

Figure 36, a One-Way ANOVA was conducted and it showed that the ATD for the *Baseline* (*N* = 96, *M* = 25.23, *SD* = 9.01) and *Mixed Traffic* (*N* = 96, *M* = 25.37, *SD* = 7.99) was similar and increased for *CAV* (*N* = 96, *M* = 28.00, *SD* = 8.39) scenario, in that order, but the ATD between these categories was statistically significantly similar, $F(2, 45) = 0.51$, $p = 0.603$.

By analysing the graph for the ATD on the *FirstSlip*, it was observed that the ATD measured for *Mixed Traffic* and *CAV* simulation category was higher than *Baseline* by ~18% and ~32%, respectively. Also, the graph shows that for the *Baseline* scenario the ATD was mostly lower than the other two categories, especially during and after the DGVs movements (i.e. after 150-180 interval duration), suggesting that the closure on the *MainRoad* did not lead to queues on *FirstSlip*.

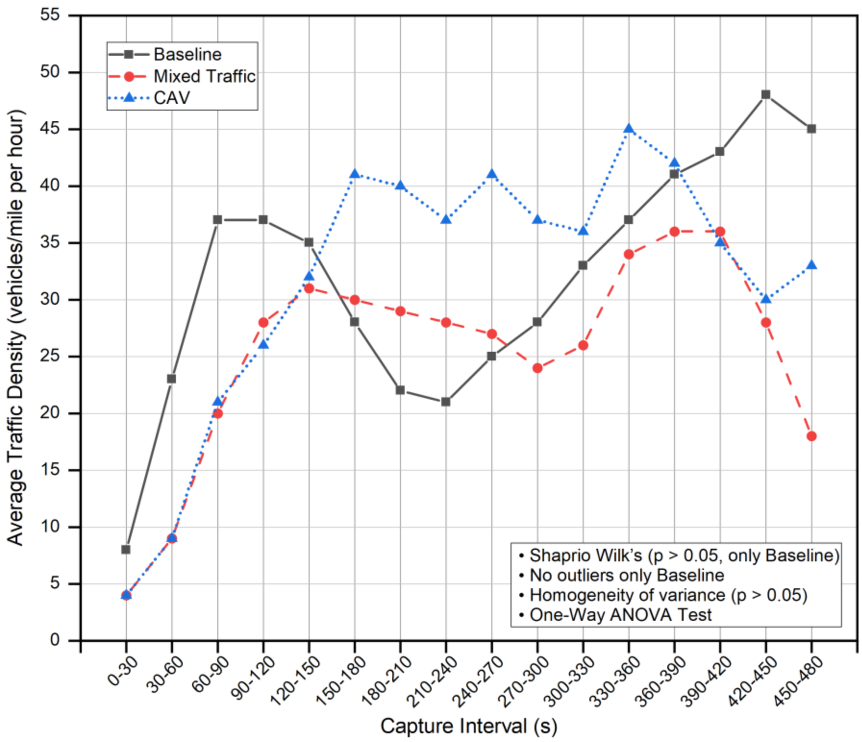


*Figure 37 ATD on SecondSlip for multi roads with single speed limit and single convoy.*

Figure 37, a One-Way ANOVA was conducted and it showed that the ATD for the *Baseline* (*N* = 16, *M* = 25.237, *SD* = 9.01) and *Mixed Traffic* (*N* = 16, *M* = 25.37, *SD* = 7.99) was similar and decrease for *CAV* (*N* = 16, *M* = 28.00, *SD* = 8.39) scenario, in that order, but the ATD between these categories was statistically significantly similar, $F(2, 45) = 1.99$, $p = 0.148$.

Although the statistical analysis stated the similarities between the three categories on *SecondSlip*, by observing the graph different flow patterns are observed. It could be seen that over all the ATD on *Mixed Traffic* was ~19% lower than the other two categories. For *Baseline* the ATD increased drastically following the closure of the traffic signal, peaking at 49 vehicles/mi flow. For *CAV* simulation category, the ATD increased drastically, stabilising during the dynamic gap generation procedure with ATD $\pm 40$ vehicles/mi per hour, before plummeting.

Overall, it could be implied that the ATD between the three categories, irrespective of the road section, diverged at the handling process of the DGVs. As no traffic closures were required the *Mixed Traffic* and *CAV* performed better than *Baseline* and more or less similar in vehicle flow patterns, except on *SecondSlip*. *CAV* category's improved performance in handling large volume of traffic could be due to the fact that all vehicles were simulated as connected with comparatively reduced headway and awareness of neighbouring vehicles.

### 4.6.2.3.2. AVTT Analysis

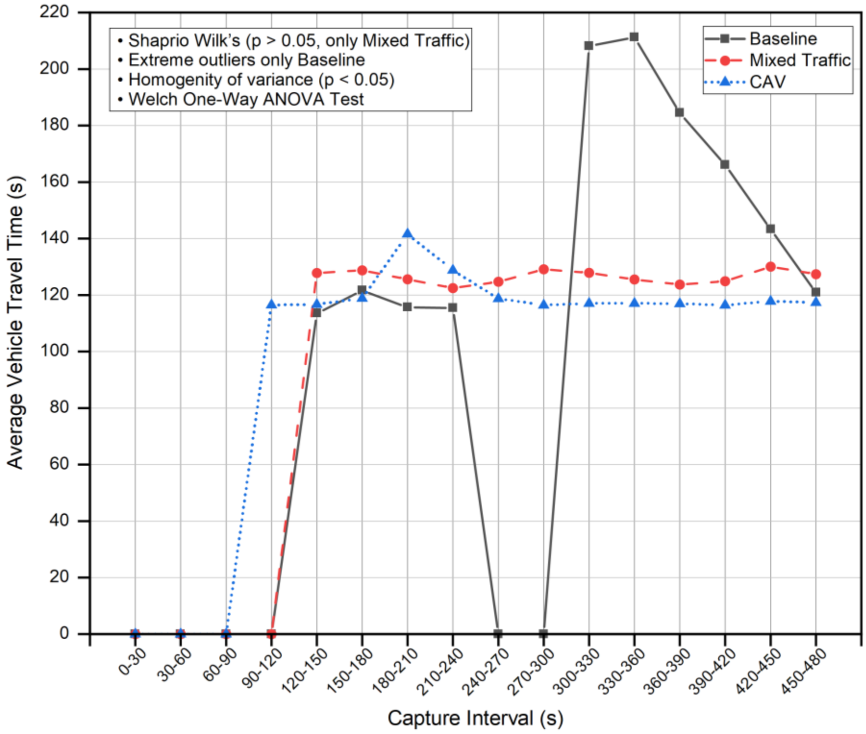


*Figure 38 AVTT on MainRoad for multi roads with single speed limit and single convoy.*

Figure 38, a Welch's One-Way ANOVA with Games-Howell post-hoc testing was performed. The AVTT on *MainRoad* was statistically significantly different between the three categories, Welch's $F(2, 14.89) = 6.25$, $p = 0.011$. The AVTT decreased from *Baseline* ($N = 10$, $M = 150.01$, $SD = 39.42$), to *Mixed Traffic* ($N = 12$, $M = 126.48$, $SD = 2.33$), and to *CAV* ($N = 13$, $M = 119.98$, $SD = 7.28$), in that order. Table 29 shows the post-hoc test results between the categories.

Table 29 Multiple comparisons between the categories using Games-Howell post-hoc test

| **Dependent Variable: Main Road AVTT** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 21.17 | 0.198 | -11.29 | 58.35 |
| | CAV | 30.02 | 0.093 | -4.91 | 64.96 |
| **MixedTraffic** | Baseline | -23.52 | 0.198 | -58.35 | 11.29 |
| | CAV | 6.49* | 0.021 | 0.95 | 12.04 |
| **CAV** | Baseline | -30.02 | 0.093 | -64.96 | 4.91 |
| | MixedTraffic | -6.49* | 0.021 | -12.04 | -0.95 |

By observing the graph, different AVTT patters were observed. The maximum AVTT observed for the *Baseline* was measured at ~211 seconds, in comparison to ~130 seconds for *Mixed Traffic* and ~142 for *CAV* scenarios, i.e. a decrease of ~38% and ~31% respectively, during the DGVs escorting procedures. The AVTT for *Mixed Traffic* performed ~3% better than *CAV* simulation. Overall, AVTT for the *Mixed Traffic* performed better than other two categories with a lowest standard deviation during the simulation.

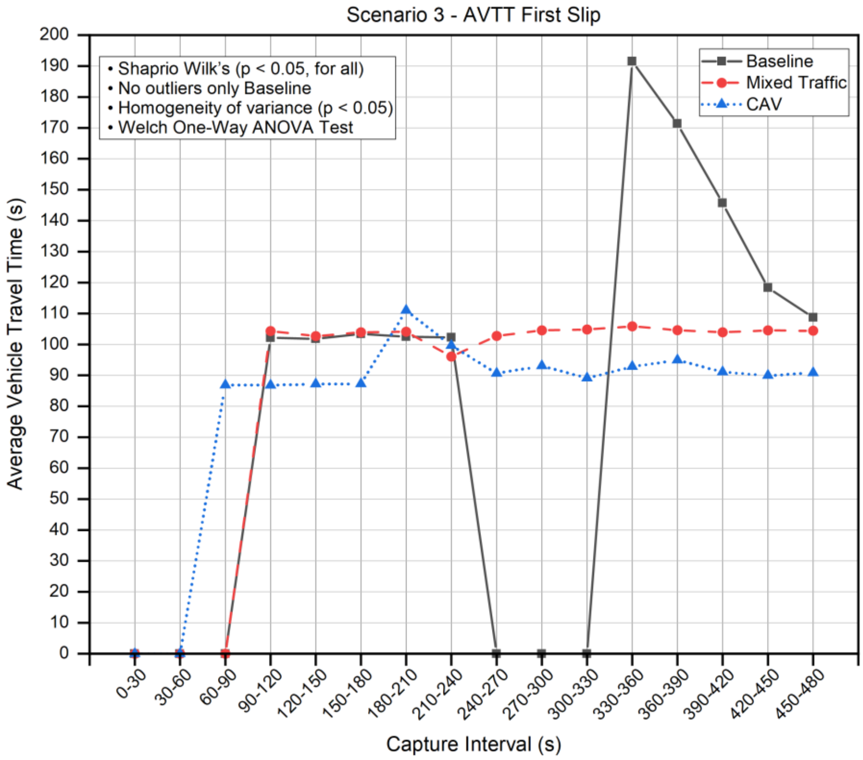


*Figure 39 AVTT on FirstSlip for multi roads with single speed limit and single convoy.*

Figure 39, a Welch's One-Way ANOVA with Games-Howell post-hoc testing was performed. The AVTT on *FirstSlip* was statistically significantly different between the three categories, Welch's $F(2, 15.67) = 20.24$, $p < 0.005$. The AVTT decreased from *Baseline* (*N* = 10, *M* = 124.77, *SD* = 33.09), to *Mixed Traffic* (*N* = 13, *M* = 103.60, *SD* = 2.40), and to *CAV* (*N* = 14, *M* = 92.22, *SD* = 6.47), in that order. Table 30 shows the post-hoc test results between the categories.

Table 30 Multiple comparison between the categories using Games-Howell post-hoc test

| **Dependent Variable: First Slip AVTT** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 21.17 | 0.163 | -8.06 | 50.40 |
| | CAV | 32.54* | 0.031 | 3.20 | 61.87 |
| **MixedTraffic** | Baseline | -21.17 | 0.163 | -50.40 | 8.06 |
| | CAV | 11.37* | 0.000 | 6.60 | 16.13 |
| **CAV** | Baseline | -32.54* | 0.031 | -61.87 | -3.20 |
| | MixedTraffic | -11.37* | 0.000 | -16.13 | -6.60 |

On the *FirstSlip*, the maximum AVTT for the *Baseline* was measured at ~192 seconds, in comparison to ~106 seconds for *Mixed Traffic* and ~111 for *CAV* scenarios, i.e. a decrease of ~45% and ~42% respectively, during the DGVs escorting procedures. The AVTT for *Mixed*

*Traffic* performed ~4% better than *CAV* simulation. Overall, AVTT for the *Mixed Traffic* performed better than other two categories with a lowest standard deviation during the simulation.

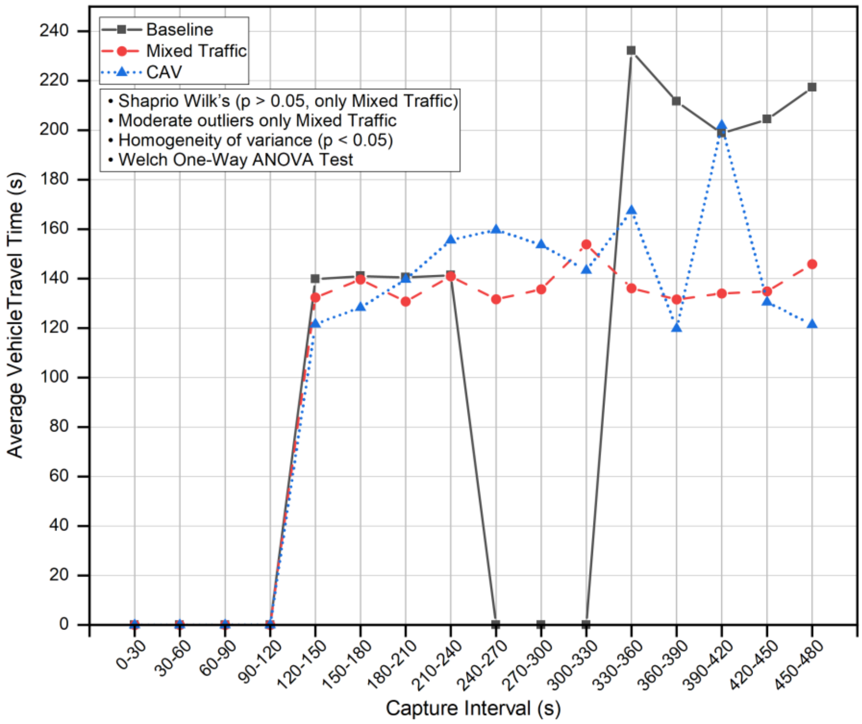


*Figure 40 AVTT on SecondSlip for multi roads with single speed limit.*

Figure 40, a Welch's One-Way ANOVA with Games-Howell post-hoc testing was performed. The AVTT on *SecondSlip* was statistically significantly different between the three categories, Welch's $F(2, 13.42) = 5.61$, $p < 0.017$. The AVTT decreased from *Baseline* ($N = 9$, $M = 180.74$, $SD = 39.08$), to *CAV* ($N = 12$, $M = 145.23$, $SD = 24.12$), and to *Mixed Traffic* ($N = 12$, $M = 137.29$, $SD = 6.87$), in that order. Table 31 shows the post-hoc tests between the categories.

Table 31 Multiple comparison between categories using Games-Howell post-hoc test

| **Dependent Variable: Second Slip AVTT** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 43.45* | 0.025 | 6.14 | 80.76 |
| | CAV | 35.51 | 0.078 | -3.69 | 74.72 |
| **MixedTraffic** | Baseline | -43.45* | 0.025 | -80.76 | -6.14 |
| | CAV | -7.94 | 0.533 | -27.10 | 11.21 |
| **CAV** | Baseline | -35.51 | 0.078 | -74.72 | 3.69 |
| | MixedTraffic | 7.94 | 0.533 | -11.21 | 27.10 |

On the *SecondSlip*, the maximum AVTT for the *Baseline* was measured at ~232 seconds, in comparison to ~154 seconds for *Mixed Traffic* and ~202 for *CAV* scenarios, i.e. a decrease of ~34% and ~13% respectively, during the DGVs escorting procedures. The AVTT for *Mixed*

*Traffic* performed ~24% better than *CAV* simulation. Overall, AVTT for the *Mixed Traffic* performed better than other two categories with a lowest standard deviation during the simulation.

### 4.6.2.3.3. AMQL Analysis

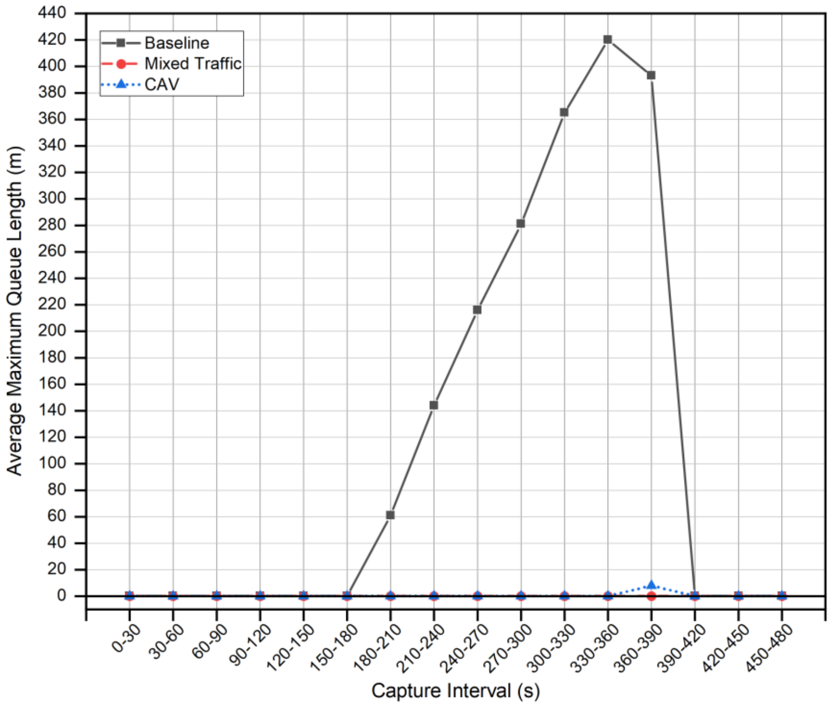


*Figure 41 AMQL on MainRoad section of multi road with single speed limit layout.*

As observed in Figure 41, the AMQL on the *MainRoad* was observed to be zero for *Mixed Traffic* and ~8 meters for *CAV* in comparison to *Baseline* where AMQL was observed to be ~248 meters, during the tunnel closure.

No queues were observed on the *FirstSlip* for any of the three scenarios for AMQL analysis.

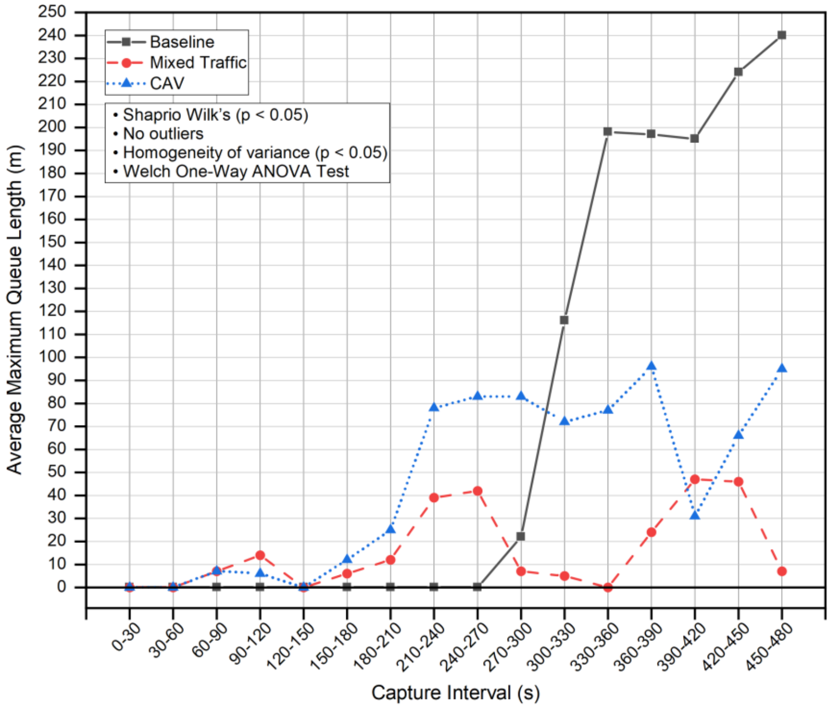


*Figure 42 AMQL on SecondSlip section of multi road with single speed limit layout.*

Figure 42, a Welch's One-Way ANOVA with Games-Howell post-hoc testing was performed. The AMQL on *SecondSlip* was statistically significantly different between the three categories, Welch's $F(2, 23.88) = 6.05$, $p = 0.007$. The AMQL decreased from *Baseline* ($N = 16$, $M = 74.75$, $SD = 99.95$), to *CAV* ($N = 16$, $M = 46.12$, $SD = 38.40$), and to *Mixed Traffic* ($N = 16$, $M = 16.18$, $SD = 17.76$), in that order. Table 32 shows the post-hoc test between the categories.

Table 32 Multiple comparison between categories using Games-Howell post-hoc test

| **Dependent Variable: Second Slip AMQL** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 58.56 | 0.084 | -6.94 | 124.07 |
| | CAV | 28.62 | 0.544 | -39.28 | 96.53 |
| **MixedTraffic** | Baseline | -58.56 | 0.084 | -124.07 | 6.94 |
| | CAV | -29.93* | 0.026 | -56.58 | -3.28 |
| **CAV** | Baseline | -28.62 | 0.544 | -96.53 | 39.28 |
| | MixedTraffic | 29.93* | 0.026 | 3.28 | 56.58 |

On *SecondSlip*, the AMQL averaged at ~171 meters for *Baseline* in comparison to ~57 meters for *CAV* and ~22 meters *Mixed Traffic*, leading to a significant traffic queue improvement of ~67% and 87%, respectively. Comparing the improvement between the *CAV* and *Mixed Traffic*, the AMQL for latter decreased by ~61%.

## 4.6.2.4. Multiple Roads and Convoys with Single Speed Limit

Figure 43 to Figure 50 show the ATD, AVTT and AMQL analysis for multiple road layout with multiple *convoys* on *MainRoad* (50 mph), *FirstSlip* (40 mph) and *SecondSlip* (40 mph) roads, to determine if the measurements on the road sections were statistically significantly different between *Baseline*, *Mixed Traffic* and *CAV* categories. The Shaprio Wilk's test was conducted for normality, along with boxplot analysis for outliers and homogeneity of variance was analysed using Leven's test.

### 4.6.2.4.1. ATD Analysis

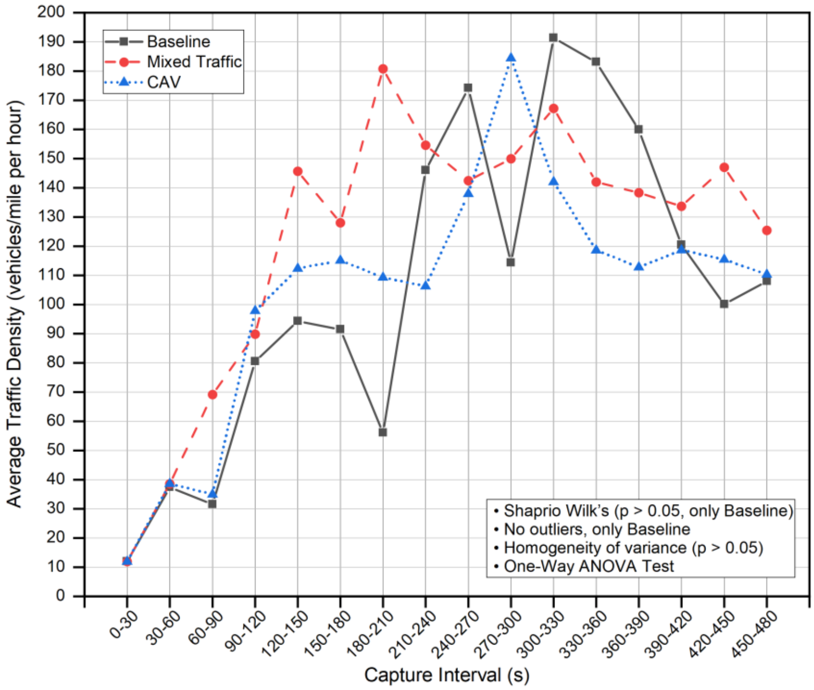


*Figure 43 ATD on MainRoad for multiple convoys on multi roads with single speed limit.*

Figure 43, a One-Way ANOVA test was performed. The ATD decreased from *Mixed Traffic* ($N$ = 16, $M$ = 122.81, $SD$ = 46.64) to *Baseline* ($N$ = 16, $M$ = 106.18, $SD$ = 54.86), and to *CAV* ($N$ = 16, $M$ = 104.12, $SD$ = 42.72), but ATD was statistically significantly similar between the three categories, $F(2, 45)$ = 0.719, $p$ = 0.493. The *Mixed Traffic* category was able to accommodate ~18% more traffic flow in comparison to *CAV* and ~16% in comparison to *Baseline* category.

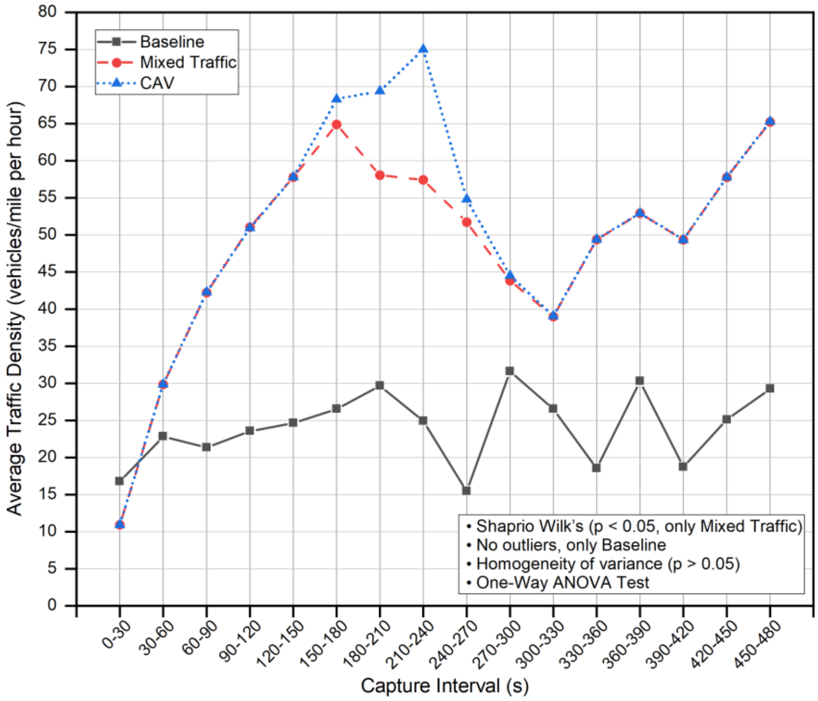


*Figure 44 ATD on FirstSlip for multiple convoys on multi roads with single speed limit.*

Figure 44, a One-Way ANOVA testing was performed with Tukey's post-hoc was performed. The ATD increased from *Baseline* (*N* = 16, *M* = 24.25, *SD* = 4.97) to *Mixed Traffic* (*N* = 16, *M* = 48.81, *SD* = 13.72), and to *CAV* (*N* = 16, *M* = 51.06, *SD* = 15.94) but ATD was statistically significantly different between the three categories, $F(2, 45) = 22.72$, $p < 0.005$. Table 33 shows the post-hoc test results between the categories.

Table 33 Multiple comparison between categories using Tukey's post-hoc test

| **Dependent Variable: First Slip ATD** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | -24.56* | 0.000 | -35.25 | -13.86 |
| | CAV | -26.81* | 0.000 | -37.50 | -16.11 |
| **MixedTraffic** | Baseline | 24.56* | 0.000 | 13.86 | 35.25 |
| | CAV | -2.25 | 0.867 | -12.94 | 8.44 |
| **CAV** | Baseline | 26.81* | 0.000 | 16.11 | 37.50 |
| | MixedTraffic | 2.25 | 0.867 | -8.44 | 12.94 |

The ATD on *Mixed Traffic* and *CAV* was improved by ~104% and ~112%, respectively, in comparison to *Baseline* where maximum traffic density was measure at 32 vehicles/mi per hour as opposed to 75 vehicles/mi per hour for *CAV*.

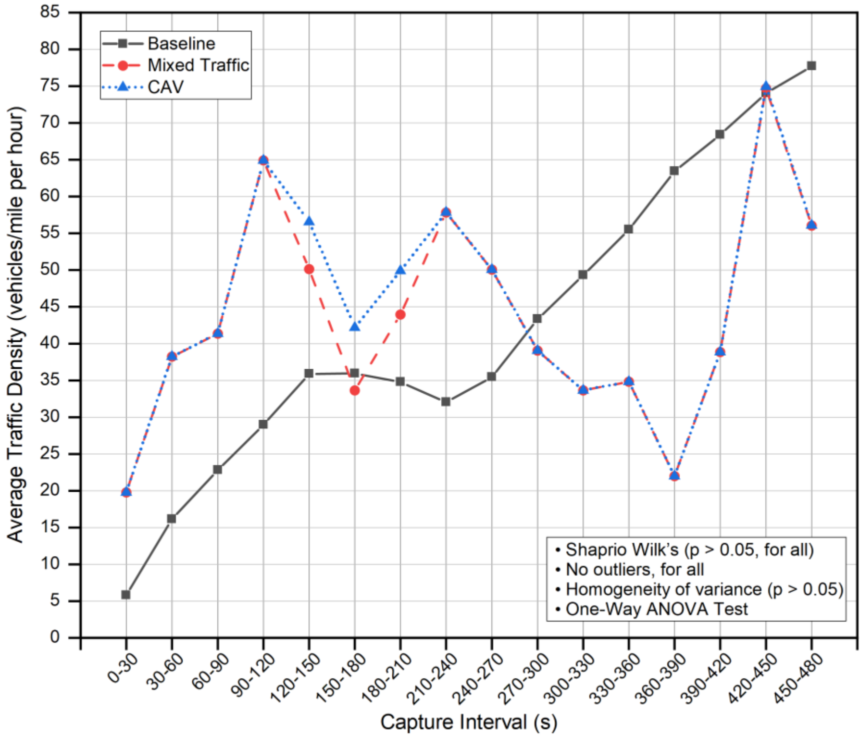


*Figure 45 ATD on SecondSlip for multiple convoys on multi roads with single speed limit.*

Figure 45, a One-Way ANOVA testing was performed. The ATD increased from *Baseline* (*N* = 16, *M* = 42.43, *SD* = 20.73) to *Mixed Traffic* (*N* = 16, *M* = 43.75, *SD* = 14.71), and to *CAV* (*N* = 16, *M* = 45.06, *SD* = 14.84) but ATD was not statistically significantly different between the three categories, $F(2, 45) = 0.095$, $p = 0.909$.

Although the ATD between categories were same, for *Baseline* category showed the upward trend following the closure of traffic on *SecondSlip*, in comparison to other two categories simulating dynamic gaps formulation.

### 4.6.2.4.2. AVTT Analysis

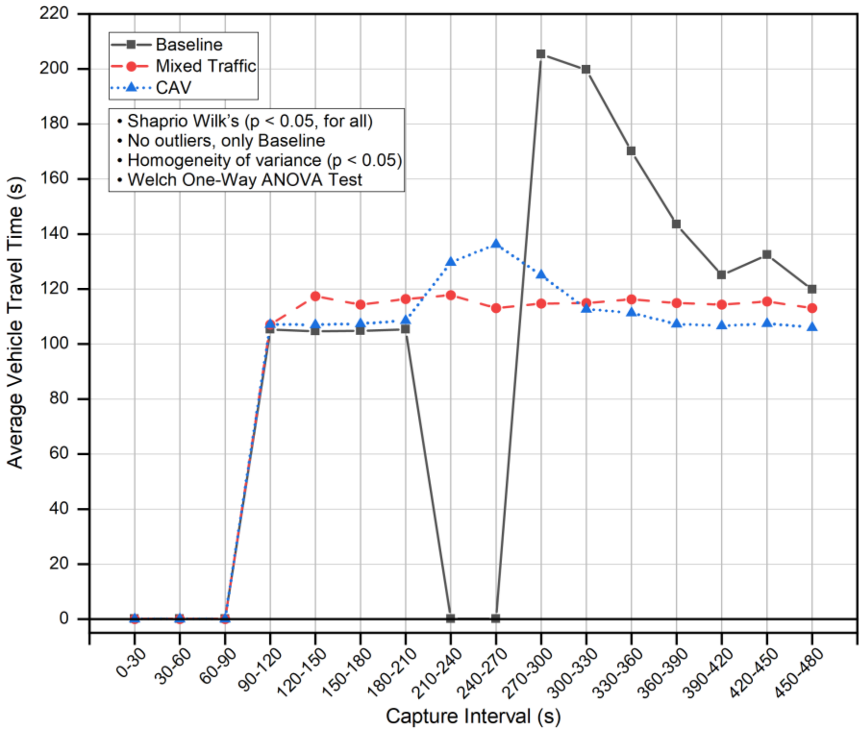

*Figure 46 AVTT on MainRoad for multiple convoys on multi roads with single speed limit.*

Figure 46, a Welch's One-Way ANOVA testing was performed with Game-Howell post-hoc testing. The AVTT decreased from *Baseline* (*N* = 11, *M* = 137.79, *SD* = 37.79) to *Mixed Traffic* (*N* = 13, *M* = 114.59, *SD* = 2.67), and to *CAV* (*N* = 13, *M* = 113.22, *SD* = 10.17), but AVTT was statistically significantly similar between the three categories, Welch's $F(2, 15.45) = 2.09$, $p < 0.156$.

Although similar, the pattern of AVTT was different. The *Mixed Traffic* and *CAV* AVTT showed more uniform travel times as compared to *Baseline* category. The maximum AVTT observed for the *Baseline* was measured at ~138 seconds, in comparison to ~115 seconds for *Mixed Traffic* and ~113 for *CAV* scenarios, i.e. a decrease of ~16% and ~18% respectively, during the DGVs escorting procedures. The AVTT for *CAV* performed marginally better than *Mixed Traffic* by ~2%. Another important point to note was for *Baseline*, it took ~210 seconds since the tunnel closure to flatten AVTT, in comparison to ~120 seconds for *CAV*, as observed, an improvement of 43% in efficiently of managing the flow of DGVs.

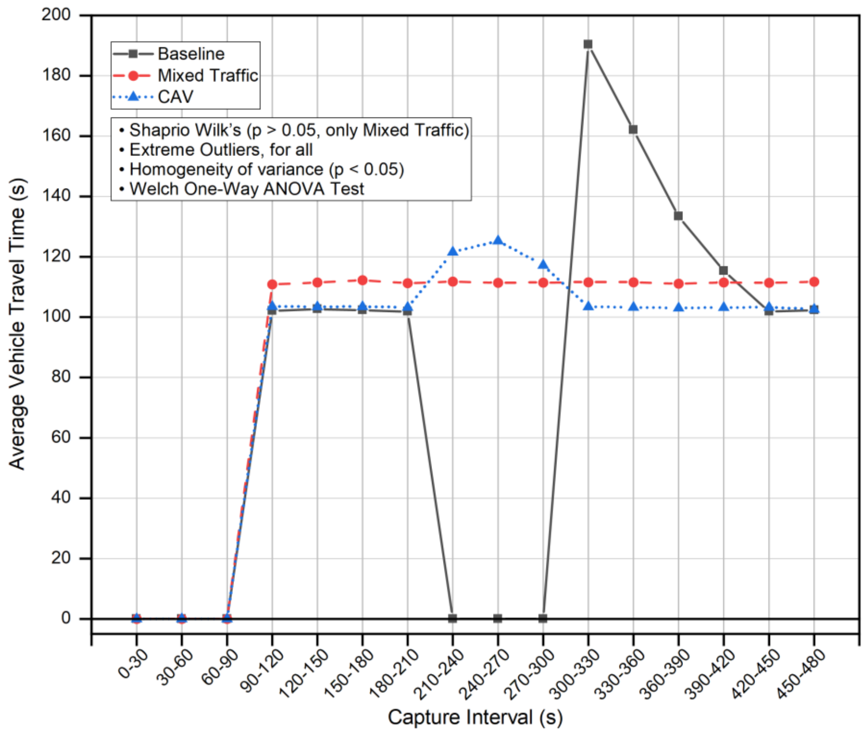


*Figure 47 AVTT on FirstSlip for multiple convoys on multi roads with single speed limit.*

Figure 47, a Welch's One-Way ANOVA testing was performed with Games-Howell post-hoc testing. The AVTT decreased from *Baseline* (*N* = 10, *M* = 121.39, *SD* = 31.25) to *Mixed Traffic* (*N* = 13, *M* = 111.49, *SD* = 0.32), and to *CAV* (*N* = 13, *M* = 107.37, *SD* = 8.10), but AVTT statistically significantly similar between the three categories, Welch's $F(2, 13.73)$ = 2.07, *p* = 0.163.

Although similar, the pattern of AVTT was different. The AVTT for *Mixed Traffic* on *FirstSlip* showed least variation throughout the simulation. For the *CAV* the travel times were consistent expect during the movement of DGVs using dynamic gaps, which was on average ~12% better than that of *Baseline* category and ~3% than *Mixed Traffic*. The maximum AVTT observed for the *Baseline* was measured at ~190 seconds, in comparison to ~112 seconds for *Mixed Traffic* and ~125 for *CAV* scenarios, i.e. a decrease of ~41% and ~34% respectively, during the DGVs escorting procedures. Another important point to note was for *Baseline*, it took ~240 seconds since the tunnel closure to flatten AVTT, in comparison to ~90 seconds for *CAV*, as observed, an improvement of 63% in efficiently of managing the flow of DGVs.

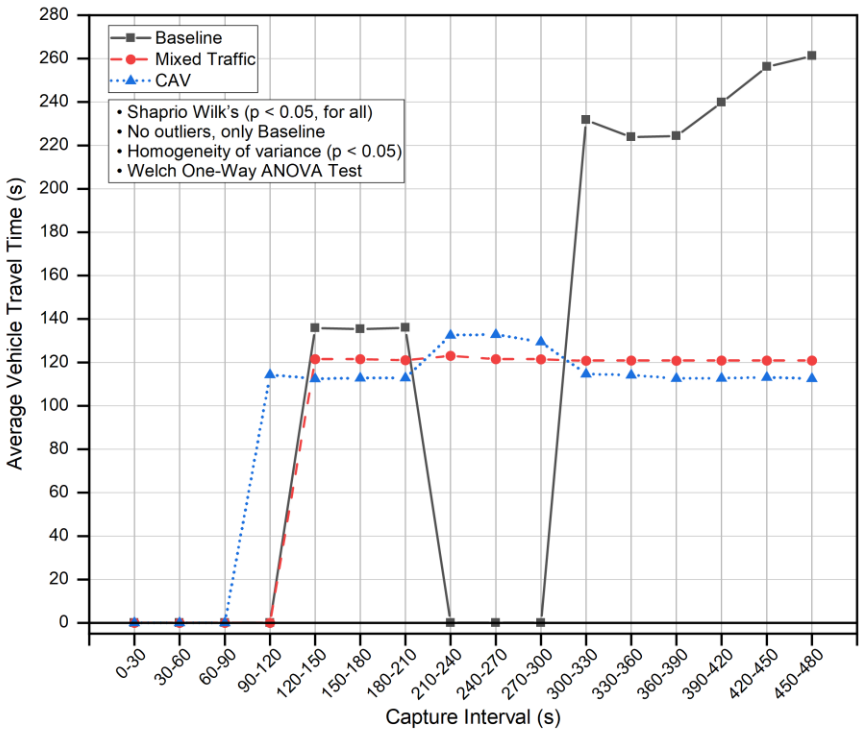


*Figure 48 AVTT on SecondSlip for multiple convoys on multi roads with single speed limit.*

Figure 48, a Welch's One-Way ANOVA testing was performed with Game-Howell post-hoc testing. The AVTT decreased from *Baseline* (*N* = 9, *M* = 204.88, *SD* = 53.41) to *Mixed Traffic*(*N* = 12, *M* = 121.25, *SD* = 0.62), and to *CAV* (*N* = 13, *M* = 117.41, *SD* = 8.13), but AVTT was statistically significantly different between the three categories, $F(2, 12.86) = 11.86$, $p$ = 0.001. Table 34 shows the post-hoc test results for comparisons between the categories.

Table 34 Multiple comparison between the categories using Game-Howell post-hoc test

| **Dependent Variable: Second Slip AVTT** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 83.63* | 0.004 | 32.75 | 134.50 |
| | CAV | 87.47* | 0.003 | 36.52 | 138.42 |
| **MixedTraffic** | Baseline | -83.63* | 0.004 | -134.50 | -32.75 |
| | CAV | 3.84 | 0.245 | -2.18 | 9.87 |
| **CAV** | Baseline | -87.47* | 0.003 | -138.42 | -36.52 |
| | MixedTraffic | -3.84 | 0.245 | -9.87 | 2.18 |

The AVTT for *Mixed Traffic* on *FirstSlip* showed least variation throughout the simulation. For the *CAV* the travel times were consistent expect during the movement of DGVs using dynamic gaps, which was on average ~43% better than that of *Baseline* category and ~3% than *Mixed Traffic*. The maximum AVTT observed for the *Baseline* was measured at ~261 seconds, in comparison to ~123 seconds for *Mixed Traffic* and ~133 for *CAV* scenarios, i.e. a decrease of ~53% and ~49% respectively, during the DGVs escorting procedures. Another important point to note was for *CAV*, it took ~90 seconds since the dynamic gap modulation to flatten AVTT, in comparison to *Baseline* where the AVTT kept increasing on the *SecondSlip* following the tunnel closure.

### 4.6.2.4.3. AMQL Analysis

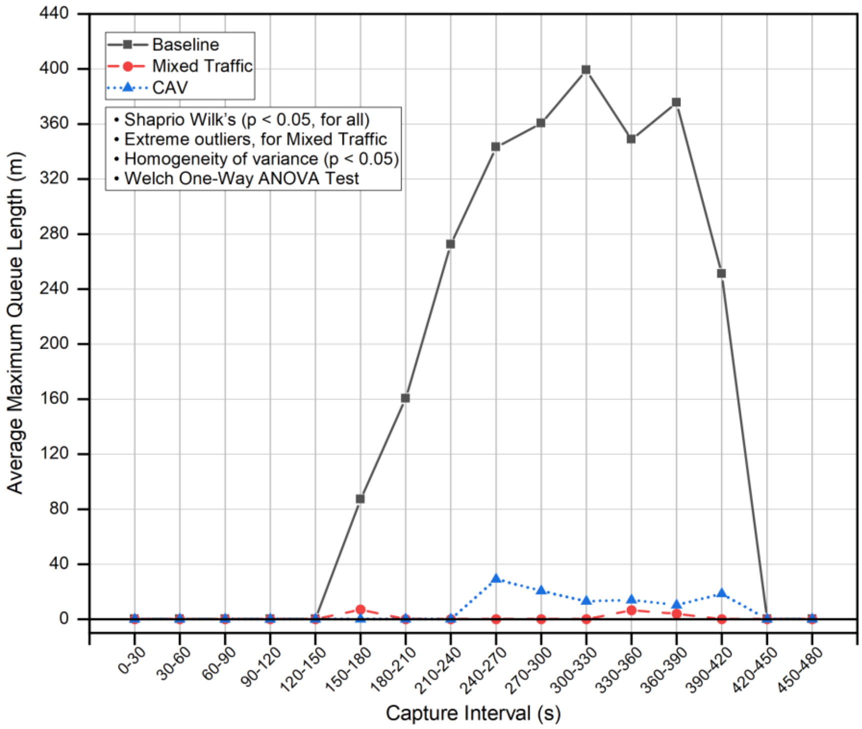


*Figure 49 AMQL on MainRoad for multiple convoys on multi roads with single speed limit.*

Figure 49, a Welch's One-Way ANOVA testing was performed with Game-Howell's post-hoc testing. The AMQL decreased from *Baseline* ($N$ = 16, $M$ = 162.31, $SD$ = 166.89) to *CAV* ($N$ = 16, $M$ = 6.5, $SD$ = 9.5), and to *Mixed Traffic* ($N$ = 16, $M$ = 1.12, $SD$ = 2.50), but AMQL was statistically significantly different between the three categories, Welch's $F(2, 21.26)$ = 9.53, $p$ = 0.001. Table 35 shows the post-hoc test results between the categories.

Table 35 Multiple comparison between categories using Games-Howell post-hoc

| **Dependent Variable: MainRoad AMQL** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 161.18* | 0.004 | 52.80 | 269.57 |
| | CAV | 155.75* | 0.005 | 47.26 | 264.23 |
| **MixedTraffic** | Baseline | -161.18* | 0.004 | -269.57 | -52.80 |
| | CAV | -5.43 | 0.101 | -11.79 | 0.92 |
| **CAV** | Baseline | -155.75* | 0.005 | -264.23 | -47.26 |
| | MixedTraffic | 5.43 | 0.101 | -0.92 | 11.79 |

As it could be observed from the graph, on *MainRoad* the AMQL for *Baseline* maxed at ~399 meters in comparison to ~7 meters for *Mixed Traffic* category and ~29 meters for *CAV*, i.e.

an overall improvement of ~98% and ~93%, respectively. The queues for *Baseline* category lasts for ~270 seconds, in comparison to ~180 seconds for *CAV*, reduction by ~33%, and ~30 seconds for *Mixed Traffic* categories, reduction by ~89%.

For the AMQL on the *FirstSlip* of the scenario no queues were observed on the *FirstSlip* during the simulations of *Baseline*, *Mixed Traffic* and *CAV* simulation categories.

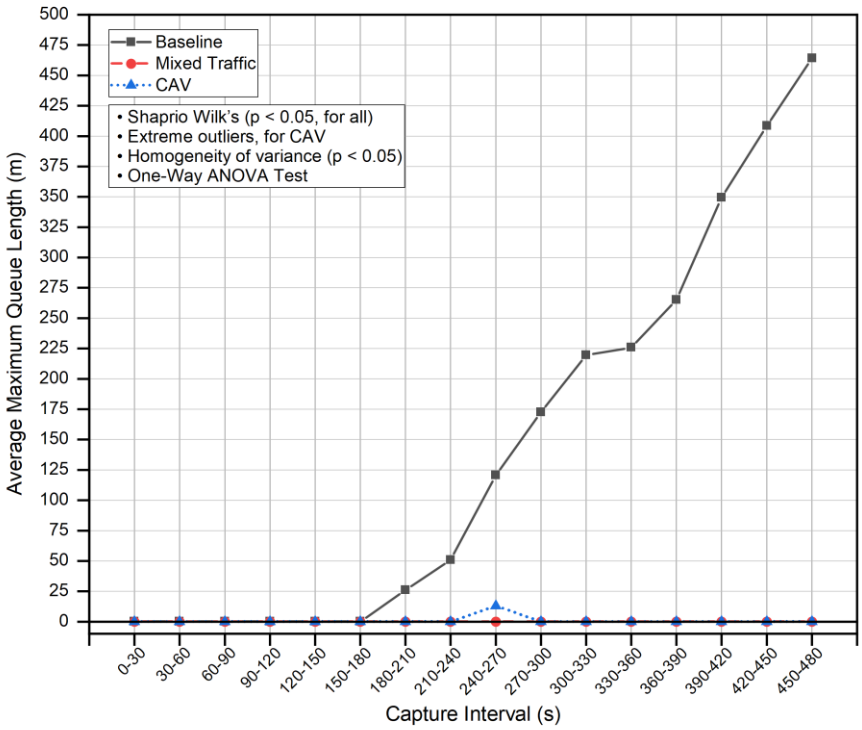


*Figure 50 AMQL on SecondSlip for multiple convoys on multi roads with single speed limit.*

From Figure 50, on *SecondSlip* the AMQL for *Baseline* maxed at ~464 meters in comparison to no queues for *Mixed Traffic* category and ~13 meters for *CAV*, i.e. an overall improvement of 100% and ~97%, respectively. The queues for *CAV* category lasts for ~30 seconds, in comparison to *Baseline* category were AMQL was not observed to flatten on *SecondSlip*.

#### 4.6.2.5. Multiple Roads and Speed Limits with Single Convoy

*Figure 51* to *Figure 58* show the ATD, AVTT and AMQL analysis for multiple road layout with multiple speed limits on *MainRoad, FirstSlip* and *SecondSlip*, but with single *convoy* on the *MainRoad*, to determine if the measurements on the road sections were statistically significantly different between *Baseline*, *Mixed Traffic* and *CAV* categories. The Shaprio Wilk's test was conducted for normality, along with boxplot analysis for outliers and homogeneity of variance was analysed using Leven's test.

#### 4.6.2.5.1. ATD Analysis

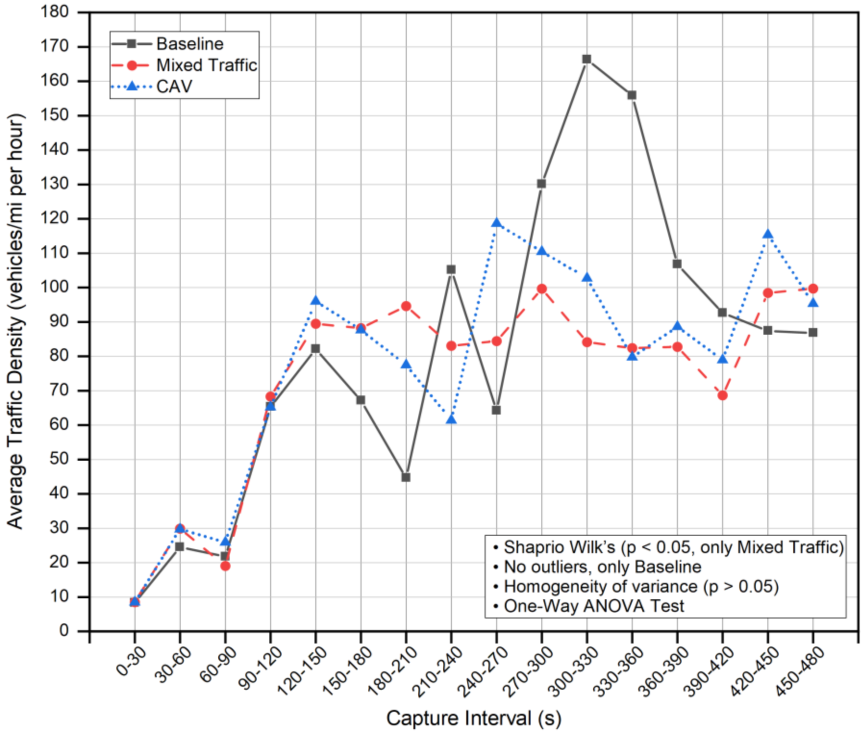


*Figure 51 ATD on MainRoad for multiple convoys on multi roads with single speed limits.*

Figure 51, a One-Way ANOVA test was performed. The ATD reduced from *Baseline* (*N* = 16, *M* = 81.81, *SD* = 45.23) to *CAV* (*N* = 16, *M* = 77.56, *SD* = 32.55), and to *Mixed Traffic* (*N* = 16, *M* = 73.75, *SD* = 28.97) but ATD was statistically significantly similar between the three categories, $F(2, 45) = 0.198$, $p = 0.821$. Although similar, *Baseline* category was able to accommodate ~11% more traffic flow in comparison to *Mixed Traffic* and ~5% in comparison to *CAV* category.

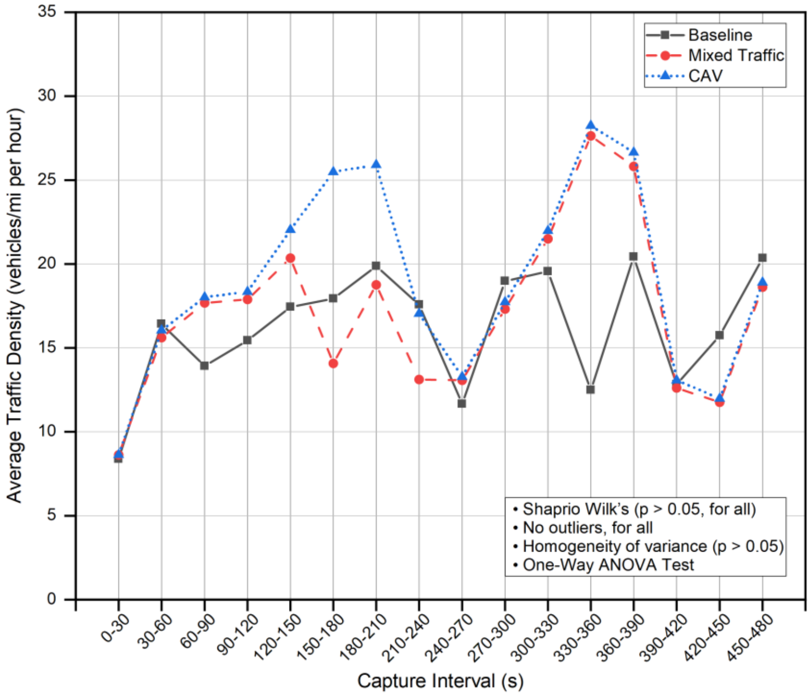


*Figure 52 ATD on FirstSlip for multiple convoys on multi roads with single speed limits.*

*Figure 52*, a One-Way ANOVA test was performed. The ATD on *FirstSlip* reduced from *CAV* (*N* = 16, *M* = 18.93, *SD* = 5.68) to *Mixed Traffic* (*N* = 16, *M* = 17.31, *SD* = 5.10), and to *Baseline* (*N* = 16, *M* = 16.12, *SD* = 3.57), but ATD was statistically significantly similar between the three categories, $F(2, 45) = 1.344$, $p = 0.271$. On *FirstSlip*, the *CAV* category was able to accommodate ~18% more traffic flow in comparison to *Baseline* and ~11% in comparison to *Mixed Traffic* category.

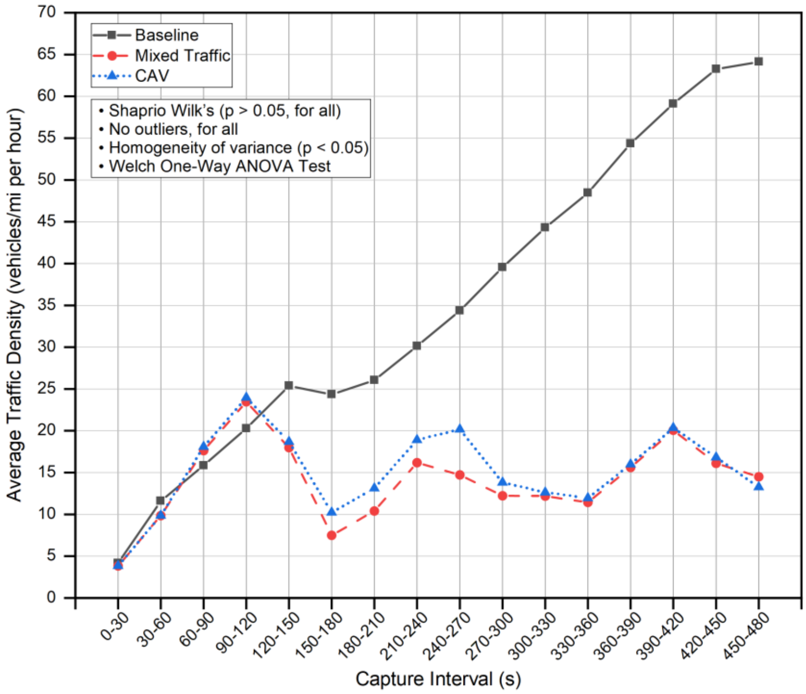


*Figure 53 ATD on SecondSlip for multiple convoys on multi roads with single speed limits.*

Figure 53, a Welch's One-Way ANOVA testing was performed with Game-Howell's post-hoc testing. The ATD on *SecondSlip* decreased from *Baseline* ($N$ = 16, $M$ = 35.18, $SD$ = 18.69) to *CAV* ($N$ = 16, $M$ = 15.12, $SD$ = 4.96), and to *Mixed Traffic* ($N$ = 16, $M$ = 13.93, $SD$ = 4.90), and ATD was statistically significantly different between the three categories, Welch's $F(2, 27.24)$ = 9.448, $p$ = 0.001. Table 36 shows the post-hoc test results between the categories.

Table 36 Multiple comparison between categories using Games-Howell post-hoc test

| **Dependent Variable: Second Slip ATD** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 21.25* | 0.001 | 8.86 | 33.63 |
| | CAV | 20.06* | 0.002 | 7.66 | 32.45 |
| **MixedTraffic** | Baseline | -21.25* | 0.001 | -33.63 | -8.86 |
| | CAV | -1.18 | 0.777 | -5.48 | 3.11 |
| **CAV** | Baseline | -20.06* | 0.002 | -32.45 | -7.66 |
| | MixedTraffic | 1.18 | 0.777 | -3.11 | 5.48 |

On the *SecondSlip*, the ATD for *Mixed Traffic* and *CAV* was able to accommodate approximately consistent traffic flow which was ~104% and ~112% lower than *Baseline*, respectively, where maximum flow of 65 vehicles/mi per hour was captured as opposed to 25 vehicles/mi per hour for *Mixed Traffic*.

# 4.6.2.5.2. AVTT Analysis

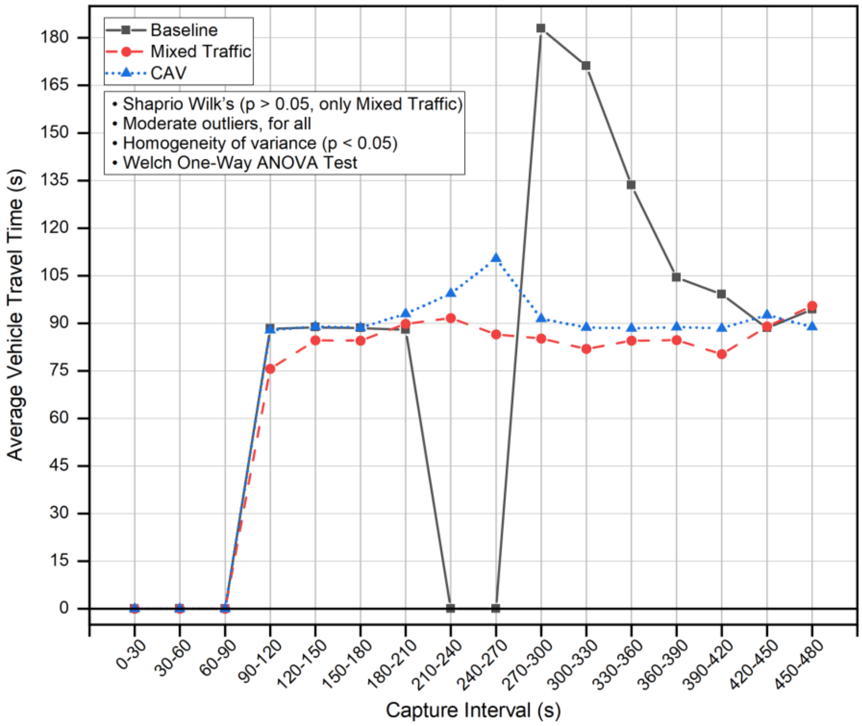


*Figure 54 AVTT on MainRoad for multiple convoys on multi roads with single speed limits.*

Figure 54, a Welch's One-Way ANOVA testing was performed with Games-Howell post-hoc testing. The AVTT on *MainRoad* decreased from *Baseline* (*N* = 11, *M* = 111.59, *SD* = 35.08) to *CAV* (*N* = 13, *M* = 91.92, *SD* = 6.25), and to *Mixed Traffic* (*N* = 13, *M* = 85.92, *SD* = 5.15), but AVTT was statistically significantly different between the three categories, Welch's $F(2, 18.79) = 5.74$, $p = 0.011$. Table 37 shows the post-hoc test results for the categories.

Table 37 Multiple comparison between categories using Games-Howell post-hoc test

| **Dependent Variable: Main Road AVTT** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 25.66 | 0.085 | -3.42 | 54.76 |
| | CAV | 19.66 | 0.206 | -9.47 | 48.81 |
| **MixedTraffic** | Baseline | -25.66 | 0.085 | -54.76 | 3.42 |
| | CAV | -6.00* | 0.035 | -11.62 | -0.37 |
| **CAV** | Baseline | -19.66 | 0.206 | -48.81 | 9.47 |
| | MixedTraffic | 6.00* | 0.035 | 0.37 | 11.62 |

The AVTT for *Mixed Traffic* on *FirstSlip* showed least variation throughout the simulation. For the *CAV* the travel times were consistent expect during the movement of DGVs using dynamic gaps, where travel time was on average ~17% lower than that of *Baseline* category but ~5% higher than *Mixed Traffic*. The maximum AVTT observed for the *Baseline* was measured at ~183 seconds, in comparison to ~96 seconds for *Mixed Traffic* and ~110 for *CAV* scenarios, i.e. a decrease of ~48% and ~40% respectively, during the DGVs escorting procedures. Another important point to note was for *Baseline*, it took ~240 seconds since the tunnel closure to flatten AVTT, in comparison to ~120 seconds for *CAV*, as observed, an improvement of 50% in efficiently of managing the flow of DGVs.

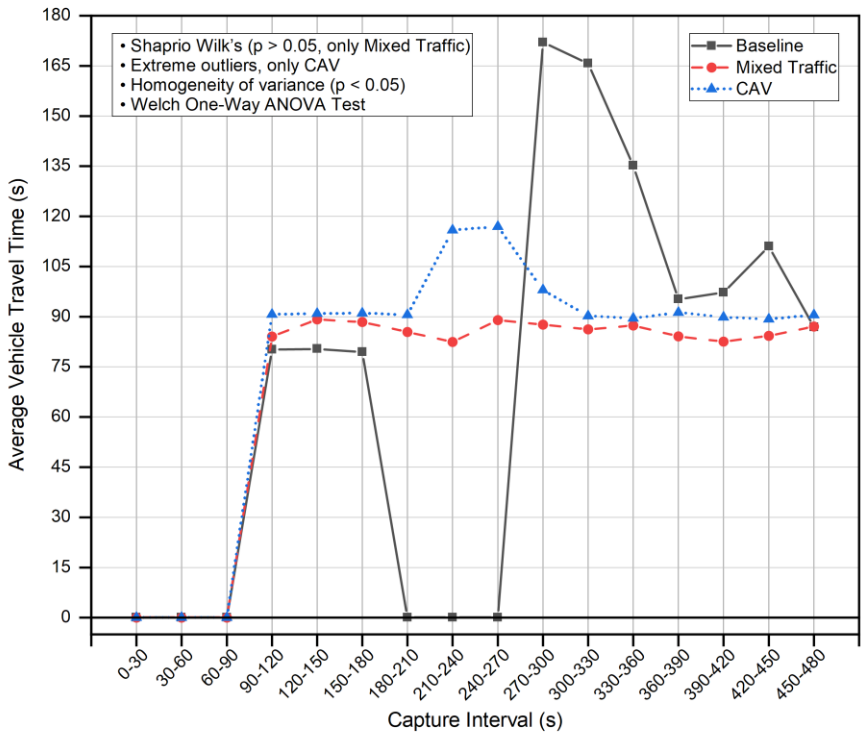


*Figure 55 AVTT on FirstSlip for multiple convoys on multi roads with single speed limits.*

Figure 55, a Welch's One-Way ANOVA testing was performed with Games-Howell post-hoc testing. The AVTT on *FirstSlip* decreased from *Baseline* (*N* = 10, *M* = 110.32, *SD* = 35.27) to *CAV* (*N* = 13, *M* = 95.00, *SD* = 9.79), and to *Mixed Traffic* (*N* = 13, *M* = 85.84, *SD* = 2.33), but AVTT was statistically significantly different between the three categories, Welch's $F(2, 14.39) = 7.33$, $p = 0.006$. Table 38 shows the post-hoc test results between the categories.

Table 38 Multiple comparison between categories using Games-Howell post-hoc test

| **Dependent Variable: First Slip AVTT** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 24.47 | 0.126 | -6.68 | 55.63 |
| | CAV | 15.32 | 0.409 | -16.11 | 46.75 |
| **MixedTraffic** | Baseline | -24.47 | 0.126 | -55.63 | 6.68 |
| | CAV | -9.15* | 0.015 | -16.50 | -1.80 |
| **CAV** | Baseline | -15.32 | 0.409 | -46.75 | 16.11 |
| | MixedTraffic | 9.15* | 0.015 | 1.80 | 16.50 |

As observed from the graph, the AVTT for *Mixed Traffic* category was consistent throughout the simulation with minimum variations in the travel times. For the *CAV*, the travel times were similar expect during the movement of DGVs using dynamic gaps, where the AVTT ~14% lower than that of *Baseline* category but ~10% higher than the *Mixed Traffic* category. The maximum AVTT observed for the *Baseline* was measured at ~172 seconds, in comparison to ~89 seconds for *Mixed Traffic* and ~117 for *CAV* scenarios, i.e. a decrease of ~48% and

~32% respectively, during the DGVs escorting procedures. Another important point to note was for *Baseline*, it took ~210 seconds since the tunnel closure to flatten AVTT, in comparison to ~120 seconds for *CAV*, as observed, an improvement of 43% in efficiently of managing the flow of DGVs.

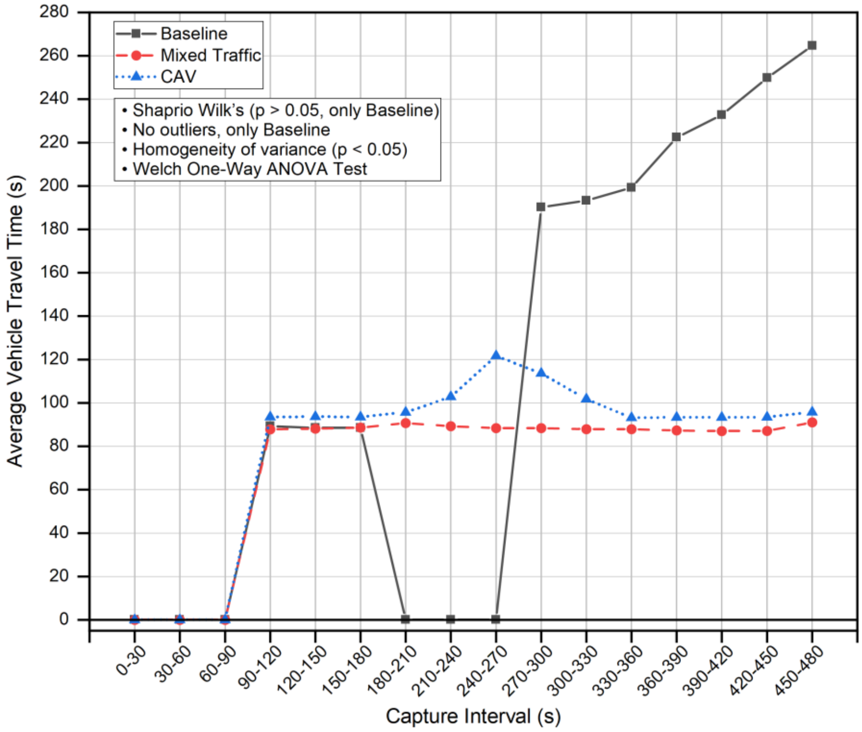


*Figure 56 AVTT on SecondSlip for multiple convoys on multi roads with single speed limits.*

*Figure 56*, a Welch's One-Way ANOVA testing was performed with Games-Howell post-hoc testing. The AVTT on *SecondSlip* decreased from *Baseline* (*N* = 10, *M* = 181.89, *SD* = 68.47) to *CAV* (*N* = 13, *M* = 98.84, *SD* = 9.29), and to *Mixed Traffic* (*N* = 13, *M* = 88.38, *SD* = 1.32), but AVTT was statistically significantly different between the three categories, Welch's $F(2, 13.95) = 16.55$, $p < 0.000$. Table 39 shows the post-hoc test between the categories.

Table 39 Multiple comparisons between categories using Games-Howell post-hoc text

| **Dependent Variable: Second Slip AVTT** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 93.50* | 0.005 | 33.04 | 153.97 |
| | CAV | 83.04* | 0.010 | 22.47 | 143.62 |
| **MixedTraffic** | Baseline | -93.50* | 0.005 | -153.97 | -33.04 |
| | CAV | -10.46* | 0.004 | -17.38 | -3.55 |
| **CAV** | Baseline | -83.04* | 0.010 | -143.62 | -22.47 |
| | MixedTraffic | 10.46* | 0.004 | 3.55 | 17.38 |

The AVTT for *Mixed Traffic* on *FirstSlip* showed least variation throughout the simulation. For the *CAV* the travel times were consistent expect during the movement of DGVs using dynamic gaps, which was on average ~46% better than that of *Baseline* category and ~52% than *Mixed Traffic*. The maximum AVTT observed for the *Baseline* was measured at ~265 seconds, in comparison to ~91 seconds for *Mixed Traffic* and ~122 for *CAV* scenarios, i.e. a decrease of ~66% and ~54% respectively, during the DGVs escorting procedures. Another important point to note was for *CAV*, it took ~150 seconds since the dynamic gap modulation to flatten AVTT, in comparison to *Baseline* where the AVTT kept increasing on the *SecondSlip* following the tunnel closure.

### 4.6.2.5.3. AMQL Analysis

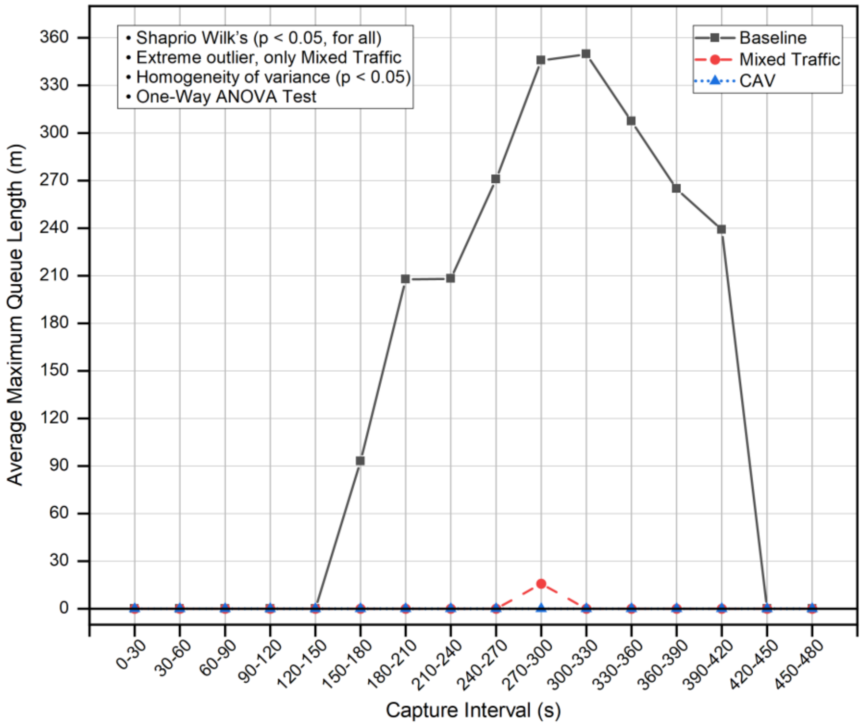


*Figure 57 AMQL on MainRoad for multiple convoys on multi roads with single speed limits.*

As observed in Figure 57 and Figure 58, the AMQL on the *MainRoad* and *SecondSlip*, respectively, was observed to be zero for *CAV*. For *Baseline*, the AMQL was observed to be ~254 meters on *MainRoad* and ~299 meters on *SecondSlip*, during the tunnel closure. For the *Mixed Traffic* category, the AMQL was observed at ~16 meters on *MainRoad* and 28 meters on *SecondSlip*. The AMQL for the *FirstSlip* was observed to be zero for all three categories. This implies that although the ATD for *Mixed Traffic* and *CAV* was significantly higher than that of *Baseline*, using the dynamic gap generation model did not lead to queue formations and kept the traffic flowing, as opposed to *Baseline* scenario where traffic had to mandatory stop to allow safe passage for DGVs via the tunnel.

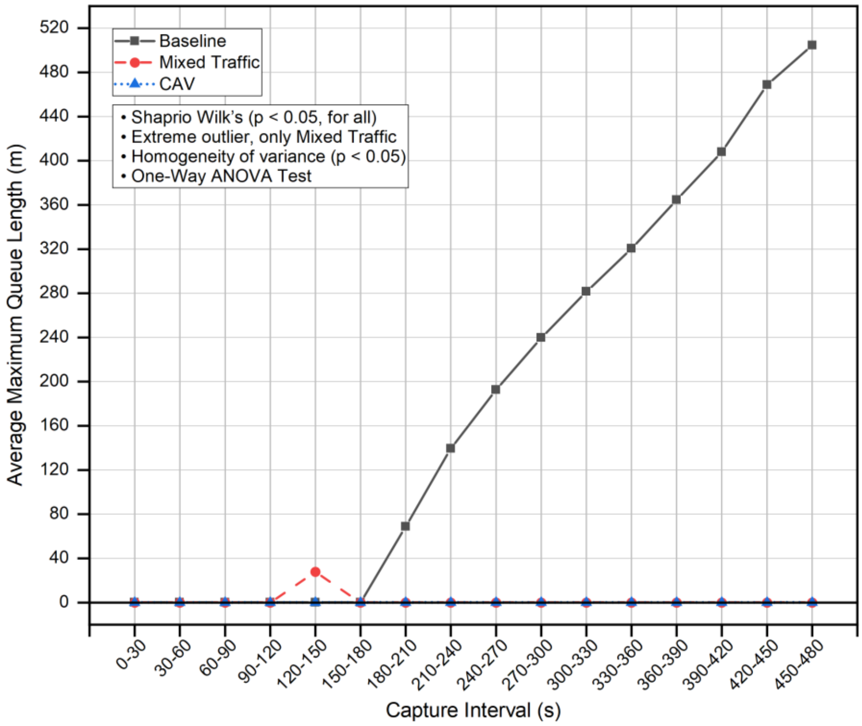


*Figure 58 AMQL on SecondSlip for multiple convoys on multi roads with single speed limits.*

#### 4.6.2.6. Multiple Roads Layout, Speed Limits and Convoys

*Figure 59* to *Figure 66* show the ATD, AVTT and AMQL analysis for multiple road layout with multiple *convoys* on *MainRoad, FirstSlip* and *SecondSlip*, and with multiple mandatory speed limits, to determine if the measurements on the road sections were statistically significantly different between *Baseline*, *Mixed Traffic* and *CAV* categories. The Shaprio Wilk's test was conducted for normality, along with boxplot analysis for outliers and homogeneity of variance was analysed using Leven's test.

### 4.6.2.6.1. ATD Analysis

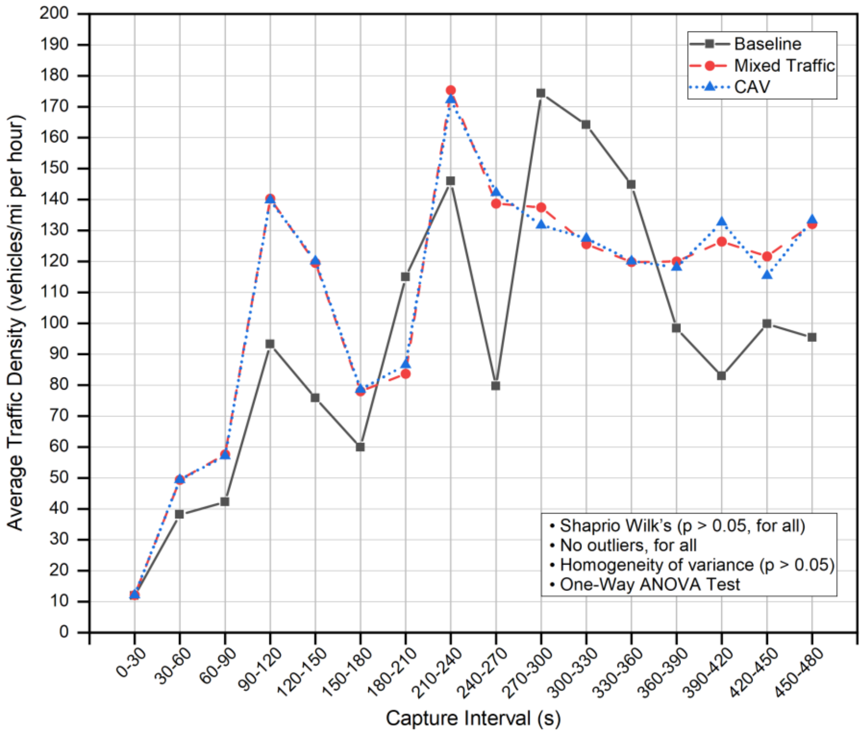


*Figure 59 ATD on MainRoad for multiple convoys on multi road layout with multi speed limits.*

Figure 59, a One-Way ANOVA test was performed. The ATD on *MainRoad* reduced from *Mixed Traffic* (*N* = 16, *M* = 108.60, *SD* = 41.51) to *CAV* (*N* = 16, *M* = 108.56, *SD* = 41.21), and to *Baseline* (*N* = 16, *M* = 95.06, *SD* = 45.78) but ATD was statistically significantly similar between the three categories, $F(2, 45) = 0.530$, $p = 0.592$.

From the graph, it was observed that for *Mixed Traffic* and *CAV* the ATD was very similar with maximum ATD observed at ~175 vehicles/mi for *Mixed Traffic* and ~172 vehicles/mi for *CAV*, which in comparison was ~15% higher than *Baseline* category.

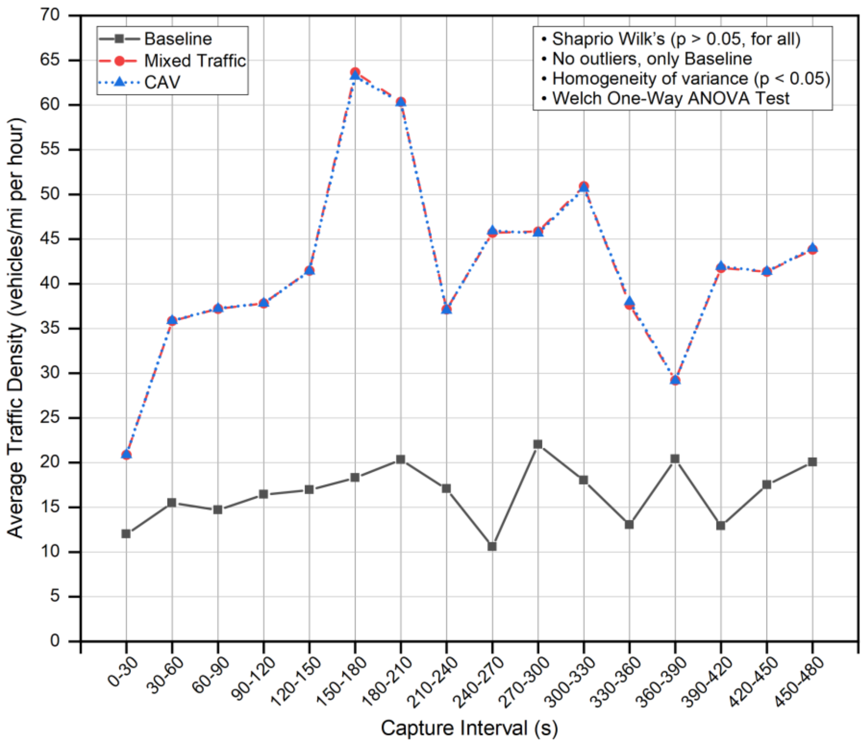

*Figure 60 ATD on FirstSlip for multiple convoys on multi road layout with multi speed limits.*

Figure 60, a Welch's One-Way ANOVA testing was performed with Games-Howell post-hoc testing. The ATD on *FirstSlip* decreased from *Mixed Traffic* ($N$ = 16, $M$ = 41.92, $SD$ = 10.48) to *CAV* ($N$ = 16, $M$ = 41.90, $SD$ = 10.39), and to *Baseline* ($N$ = 16, $M$ = 16.62, $SD$ = 3.18), but ATD was statistically significantly different between the three categories, Welch's $F(2, 23.20)$ = 76.95, $p$ < 0.000. Table 40 shows the post-hoc analysis between the categories.

Table 40 Multiple comparison between the categories using Games-Howell post-hoc test

| **Dependent Variable: First Slip ATD** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | -25.29 | 0.000 | -32.30 | -18.29 |
| | CAV | -25.27 | 0.000 | -32.21 | -18.33 |
| **MixedTraffic** | Baseline | 25.29 | 0.000 | 18.29 | 32.30 |
| | CAV | 0.023 | 1.000 | -9.07 | 9.12 |
| **CAV** | Baseline | 25.27 | 0.000 | 18.33 | 32.21 |
| | MixedTraffic | -0.023 | 1.000 | -9.12 | 9.07 |

It was observed that the ATD for *Mixed Traffic* and *CAV* again was very similar on *FirstSlip*, as on *MainRoad*, with maximum ATD observed at ~64 vehicles/mi for *Mixed Traffic* and ~63 vehicles/mi for *CAV*. Both the categories were able to accommodate ~147% higher traffic density, in comparison to *Baseline* category.

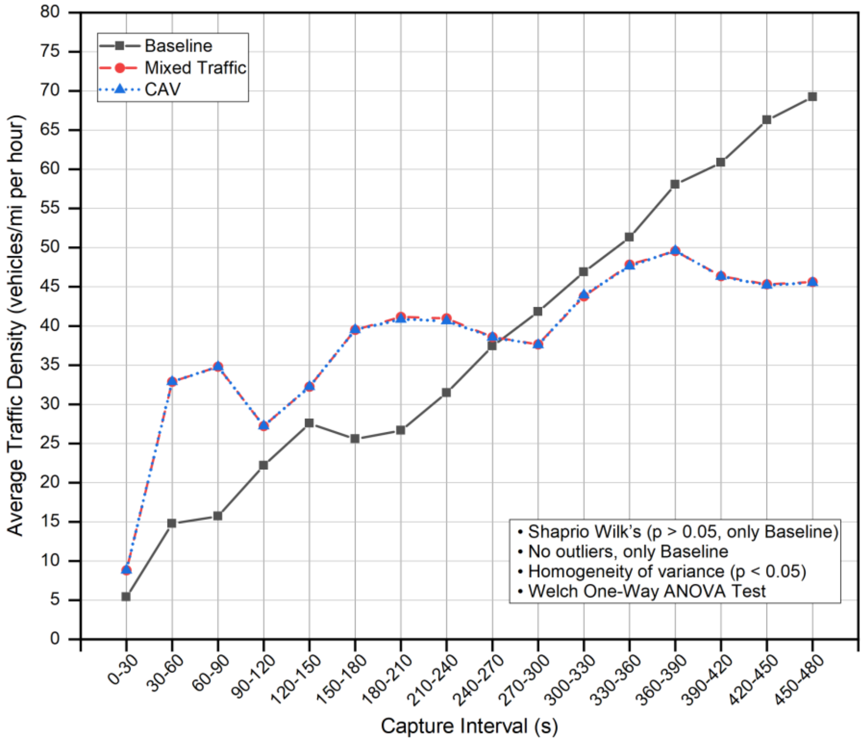


*Figure 61 ATD on SecondSlip for multiple convoys on multi road layout with multi speed limits.*

Figure 61 a One-Way ANOVA test was performed. The ATD on *SecondSlip* decreased from *Mixed Traffic* (*N* = 16, *M* = 32.27, *SD* = 10.01) to *CAV* (*N* = 16, *M* = 38.20, *SD* = 9.98), and to *Baseline* (*N* = 16, *M* = 37.56, *SD* = 19.51), but ATD was statistically significantly similar between the three categories, Welch's *F(2, 28.48)* = 0.009, *p* = 0.991.

It was observed that the ATD for all three categories was very similar on *SecondSlip*, but unlike for *Mixed Traffic* and *CAV* categories, the ATD kept rising for *Baseline* with maximum density measured at ~69 vehicles/mi per hour, as compared to ~50 vehicles/mi per hour for other two.

### 4.6.2.6.2. AVTT Analysis

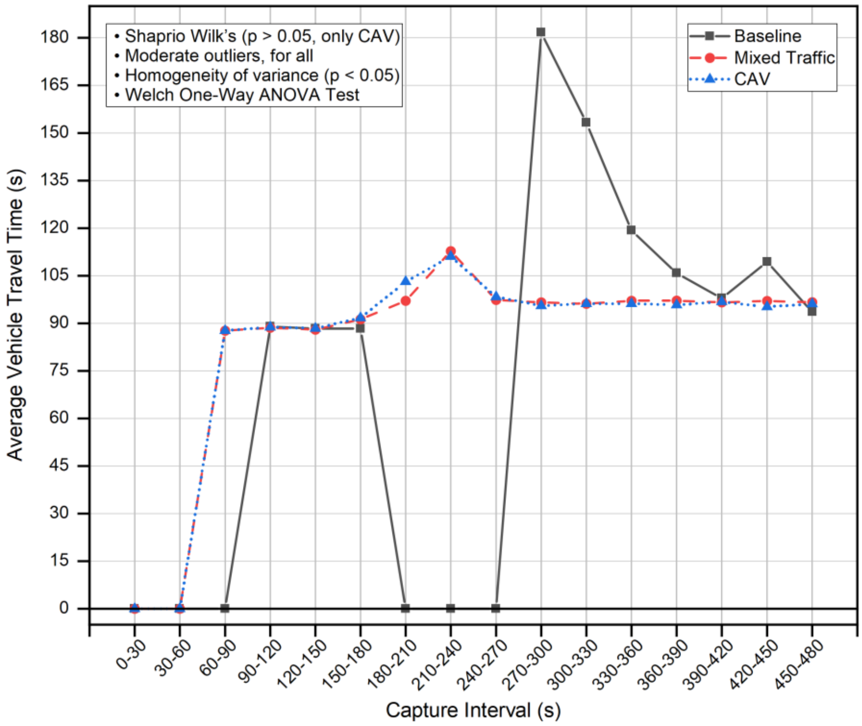


*Figure 62 AVTT on MainRoad for multiple convoys on multi roads with multi speed limits.*

Figure 62 a Welch's One-Way ANOVA test was performed. The AVTT on *MainRoad* decreased from *Baseline* (*N* = 10, *M* = 112.65, *SD* = 31.33) to *CAV* (*N* = 14, *M* = 95.77 *SD* = 6.08), and to *Mixed Traffic* (*N* = 14, *M* = 95.72, *SD* = 6.17), but AVTT was statistically significantly similar between the three categories, Welch's *F(2, 18.06)* = 1.38, *p* = 0.276.

As observed from the graph, travel time pattern differs between *Baseline* and other two categories. The *Mixed Traffic* and *CAV* categories are very similar with marginal different in mean and standard deviation. The maximum travel time observed for *Mixed Traffic* was ~113 seconds and for *CAV* ~111 seconds, in comparison to ~182 seconds for *Baseline* category. That is an improvement of ~38% in travel times for *Mixed Traffic* and *CAV* category vehicles. Also, it took ~240 seconds following the tunnel closure for the *Baseline* category to normalise travel times, in comparison to ~120 seconds for other two categories, i.e. an improvement of ~100%, when dynamic gap generation formulation was used for DGVs escorting.

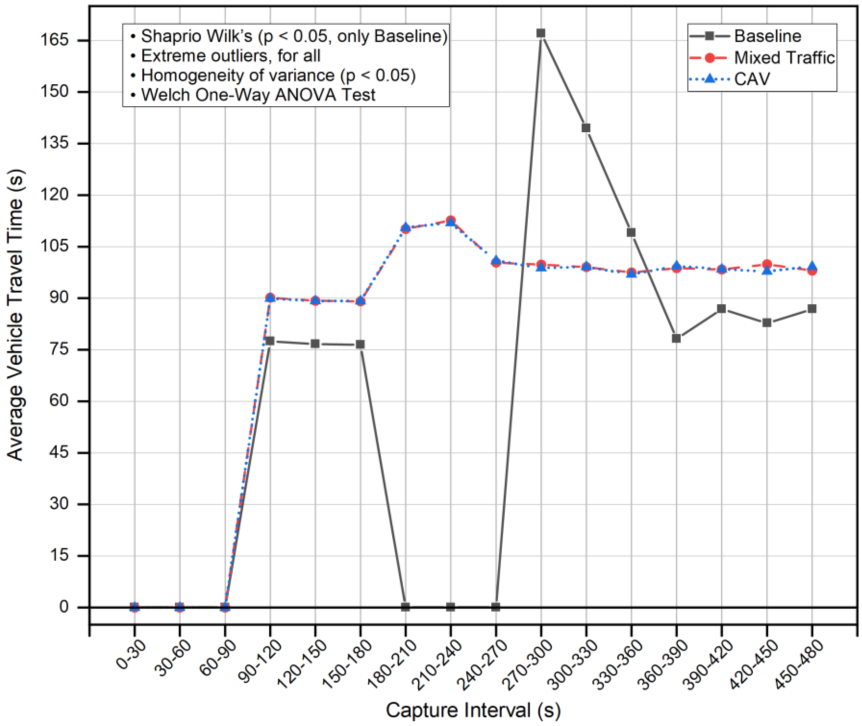


*Figure 63 AVTT on FirstSlip for multiple convoys on multi roads with multi speed limits.*

Figure 63 a Welch's One-Way ANOVA test was performed. The AVTT on *FirstSlip* decreased from *Baseline* (*N* = 10, *M* = 112.65, *SD* = 31.33) to *CAV* (*N* = 14, *M* = 95.77 *SD* = 6.08), and to *Mixed Traffic* (*N* = 14, *M* = 95.72, *SD* = 6.17), but AVTT was statistically significantly similar between the three categories, Welch's $F(2, 18.06) = 1.38$, $p = 0.276$.

Although the AVTT on *FirstSlip* was statistically similar between the three categories, as observed from the graph, travel time pattern differs between *Baseline* and other two categories. The *Mixed Traffic* and *CAV* categories are very similar with marginal different in mean and standard deviation. The maximum travel time observed for *Mixed Traffic* was ~113 seconds and for *CAV* ~112 seconds, in comparison to ~167 seconds for *Baseline* category. That is an improvement of ~48% in travel times for *Mixed Traffic* and *CAV* category vehicles. Also, it took ~210 seconds following the tunnel closure for the *Baseline* category to normalise travel times, in comparison to ~90 seconds for other two categories, i.e. an improvement of ~133%, when dynamic gap generation formulation was used for DGVs escorting.

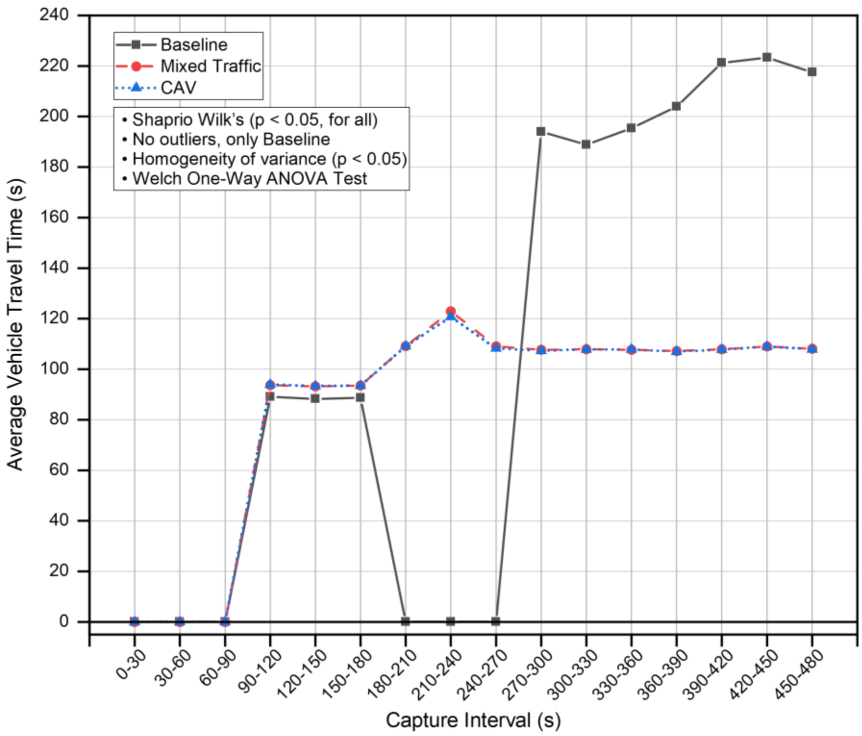


*Figure 64 AVTT on SecondSlip for multiple convoys on multi roads with multi speed limits.*

Figure 64 a Welch's One-Way ANOVA testing was performed with Games-Howell post-hoc testing. The *AVTT* on *SecondSlip* decreased from *Baseline* (*N* = 10, *M* = 171.05, *SD* = 58.0) to *Mixed Traffic* (*N* = 13, *M* = 105.93, *SD* = 8.17), and to *Baseline* (*N* = 13, *M* = 105.65, *SD* = 7.73), but *AVTT* was statistically significantly different between the three categories, Welch's $F(2, 17.55) = 6.05$, $p < 0.010$. Table 41 shows the post-hoc test results between the categories.

Table 41 Multiple comparisons between the categories using Games-Howell post-hoc test

| **Dependent Variable: Second Slip AVTT** | | | | | |
|---|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Mean Difference (I-J)** | **Sig.** | **95% Confidence Interval** | |
| | | | | **Lower Bound** | **Upper Bound** |
| **Baseline** | MixedTraffic | 65.11* | 0.015 | 13.78 | 116.43 |
| | CAV | 65.39* | 0.015 | 14.08 | 116.70 |
| **MixedTraffic** | Baseline | -65.11* | 0.015 | -116.43 | -13.78 |
| | CAV | 0.28 | 0.995 | -7.51 | 8.08 |
| **CAV** | Baseline | -65.39* | 0.015 | -116.70 | -14.08 |
| | MixedTraffic | -0.28 | 0.995 | -8.08 | 7.51 |

Although the AVTT on *SecondSlip* was statistically similar between *Mixed Traffic* and *CAV*, as observed from the graph, travel time pattern differs between *Baseline* and other two categories. The *Mixed Traffic* and *CAV* categories are very similar with marginal different in mean and standard deviation. The maximum travel time observed for *Mixed Traffic* was ~123 seconds and for *CAV* ~121 seconds, in comparison to ~223 seconds for *Baseline* category, an improvement of ~45% in travel times for *Mixed Traffic* and *CAV* category vehicles. Noted that it took ~90 seconds following the dynamic gap generation formulation for the *Mixed Traffic* and *CAV* categories to normalise travel times, in comparison to *Baseline* where the travel times kept rising, due to ever growing traffic queues, on the *SecondSlip*.

#### 4.6.2.6.3. AMQL Analysis

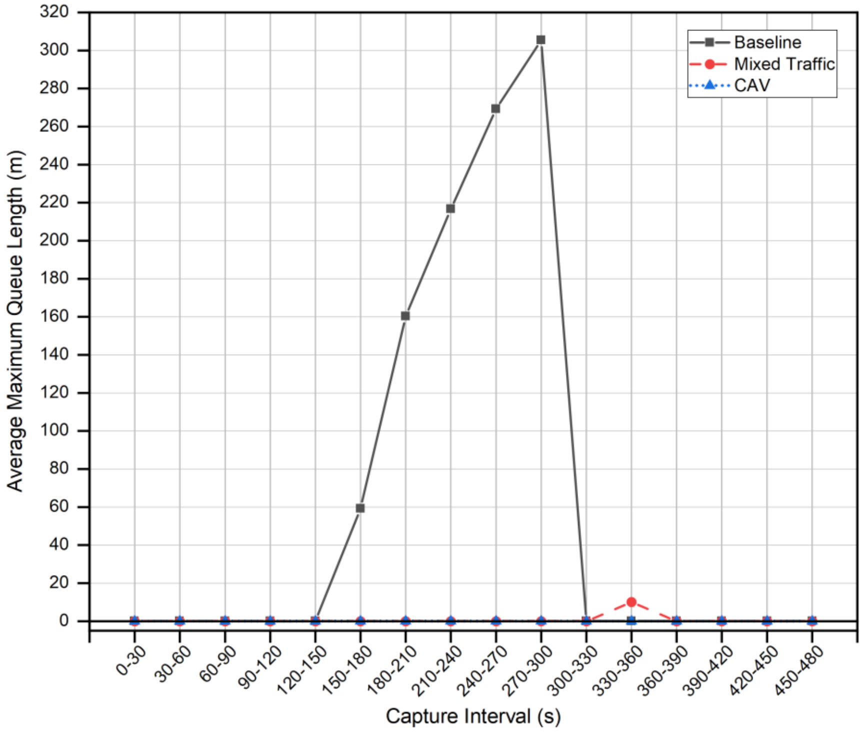


*Figure 65 AMQL on MainRoad for multiple convoys on multi road with multi speed limits.*

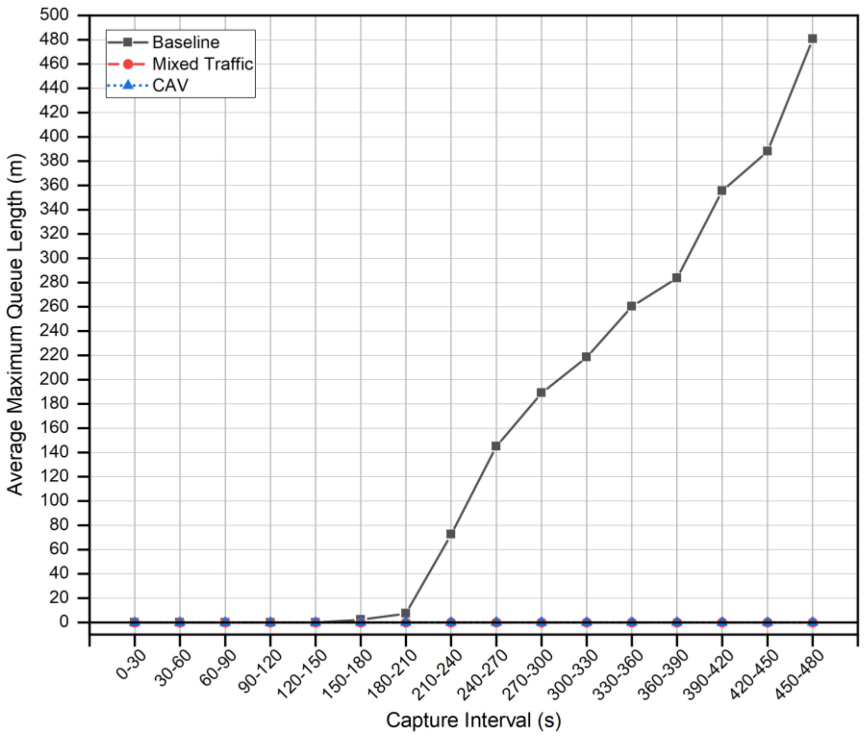

*Figure 66 AMQL on SecondSlip for multiple convoys on multi road with multi speed limits.*

As observed in Figure 65 and Figure 66 the AMQL on the *MainRoad* and *SecondSlip*, respectively, was observed to be zero for *Mixed Traffic* and *CAV* in comparison to *Baseline* where AMQL was observed to be ~202 meters on *MainRoad* and ~218 meters on *SecondSlip*, during the tunnel closure. The AMQL for the *FirstSlip* was observed to be zero for all three categories. This implies that although the ATD for *Mixed Traffic* and *CAV* was significantly higher than that of *Baseline*, using the dynamic gap generation model did not lead to queue formations and kept the traffic flowing, as opposed to *Baseline* scenario where traffic had to mandatory stop to allow safe passage for DGVs via the tunnel.

## 4.7. Conclusions

By analysing the *Phase I* results it could be stated that the C-ITS communication $rP$ locations as calculated using the mathematical model were appropriately placed to generate dynamic vehicular gaps using dynamic speed modulations effectively. It was noted that for all the different road layout scenarios the *preceding*, *convoy* and *following* vehicles travelled as anticipated, generating desired gaps to allow the *convoy* to travel in isolation. From the stepwise sequences it was observed that *preceding* and *following* vehicles were at approximately $d_{safe}$ distance as the *convoy* entered and exited the tunnel. Using the model and appropriate reset techniques, ensured that *following* vehicles now travelling at higher speeds were hold back by slower traffic in front, as shown in Figure 29. It would suggest that too early a reset would let faster vehicle approach the *convoy* before it completes its journey and diminish the generated gap between the *convoy* and *following* vehicles, and too late a reset would impact on the efficiency of travel for *following* vehicles, leading to delays, queues and congestion build ups.

By analysing the results for the *Phase II*, it could be observed that the dynamic gap generation performed overall better than *Baseline* existing technique of escorting of *DGVs* via a road tunnel in isolations It was noted that overall traffic flow on all road sections were significantly improved from *Baseline* scenario to other two scenarios. Cross verification of travel time and queue formations on per road basis between the scenarios showed that *MixedTraffic* and *CAV* scenarios benefited considerably by using dynamic gap generation model.

By observing the average vehicle counts, no statistically significant improvements were observed. Nevertheless, it was noticed that *MixedTraffic* and *CAV* scenarios were able to accommodate comparatively higher volume of traffic than the *Baseline* scenario, for the exact same road layout. This could be because of smaller headway between connected vehicles or coordinated driving behaviour as simulated by PTV Vissim based on CoEXist project in comparison to Wiedemann 99 model for conventional vehicles. This statement could be supported by another study [83] which analysed the impact of connected vehicles in improving the traffic throughput via a road tunnel network. Another interesting observation made was regarding the recovery of traffic from perturbations caused by traffic closure or dynamic gaps. It was observed that it took ~3min to recover from the disruptions for all the three traffic scenarios, but the highest congregation vehicles were observed for *CAV* scenarios, which could be due to shorter headways and standstill distances simulated than other two scenarios. Once the traffic was stabilised after ~3min, the traffic flow remained stable till the end of simulation.

Finally, by analysing the average maximum queue lengths, it was observed that the queues lengths were substantially improved by ~60% from *Baseline* to *MixedTraffic* scenario and by ~73% from *Baseline* to *CAV* scenarios. Between the *MixedTraffic* and *CAV* scenarios, the queues were improved by ~33%. These average queue reductions were significant even with the traffic volume for *MixedTraffic* and *CAV* scenarios was observed to be higher, especially when the dynamic gap generation was in progress. These queue reductions could be related to significantly improved travel times for these two traffic scenarios.

# Chapter 5

# Destructive Wave Interference Pattern

In Chapter 4 , the novel mathematical model was developed to benefit road tunnel infrastructure by identifying the strategic C-ITS geo-locations to enable autonomous escorting of DGVs using dynamic gap generation technique. Taking a step further, this chapter describes how the approach of dynamic gap generation is generalised for use as a congestion relief strategy by optimising the traffic merging at a motorway junction. The chapter details the previous studies and draws the distinction with the proposed novel approach which is inspired by the noise cancellation technique utilising destructive wave interference patterns. The traffic flow on two separate roads (main and slip) meeting at a junction is visualised as traffic-wave propagating through a road network. By identifying the traffic wave pattern of mixed vehicle types from fixed equidistant locations on the main road and the slip road, dynamic phase shifting is applied by modulating the speeds of vehicles that would otherwise approach at the junction simultaneously, leading to queue formation. This dynamic phase shifting is a crucial aspect of the proposed method as it is based on the location and length of vehicles on the road network. The results are analysed for uninterrupted flow of traffic optimising travel time, reducing congestion, and improvements in traffic throughput.

## 5.1. Literature Review

To effectively control the traffic flow on roads safely and to minimise road congestion, systems such as Active Traffic Managements (ATM) systems, smart motorways, adaptative traffic signal controls, C-ITS, are developed. The emphasis is laid on making the vehicles intelligent with the ongoing advancements in the fields of artificial intelligence and wireless technology [76], to develop telematics technology integrated with ADAS [75].

As the C-ITS technologies have advanced [142] and Vehicle-2-Vehicle (V2V) and Vehicle-2-Infrastructure (V2I) communication protocols have standardised and matured [143, 145, 148, 151], in this paper, the study is focused on improving the traffic flow by dynamically coordinating the vehicles travelling on two separate roads (*Main Road* and *Slip Road*) merging at a junction on UK motorways. The approach used is a unique take on existing coordinated and slot-based merging strategies by considering traffic flow of vehicles as traffic-wave patterns, and the collision free merging is achieved by phase shifting one of the waves (i.e. modulating velocity of a vehicle) on either road that would lead to destructive interference, in turn an uninterrupted merging. The approach is influenced by the noise cancelling mechanism and how destructive interference of two waves leads to no noise or as in this case no collision at junction but a suitable gap for an on-coming vehicle to merge.

Various congestion control measures such as lane control, variable speed limits, traffic management systems, ADAS, etc. have been discussed in great detail in past to solve the problem of road traffic congestion. The ramp metering and dynamic ramp metering [129] measures to control traffic approaching a junction have been studied using traffic signals to hold traffic using fixed time algorithms [167], responsive algorithms and proactive algorithms which utilises real-time traffic information [168]. Ramp metering algorithms have taken approaches to control traffic locally at a motorway junction [169] or in a coordinated manner spanning over a longer distance with multiple entry/exit locations [170, 171]. Although ramp metering has proven effecting in congestion control, geographic limitations, and cost of installing these systems across all the motorway network is not always a viable option.

Other approaches used to control congestion is by optimising the merging behaviour of vehicles at the road junctions. Many previous studies have analysed the merging at junctions using queuing theory and statistics, as suggested in [172] for conventional vehicles. The use of Adaptative Cruise Control (ACC) and Cooperative ACC (CACC) was also studied to control the merge behaviours at the junctions. This previous paper [173] studied the benefits of ACC by controlling longitudinal motion of vehicles on mixed traffic scenarios involving manual vehicles and vehicles fitted with ACC at different penetration rates of ACC (0%, 30%, 50% and 100%). The objective of cooperative merging was to generate a large enough gap so that a merging vehicle can change lanes without slowing down drastically.

In another study [174] three proactive traffic merging strategies were discussed for sensor-enabled cars which determined where and when the cars travelling on two separate roads (main road and ramp/slip road) should merge before approaching a junction. The study pre-determined the sequence of cars in which they should merge based on the distance, velocity or platoon-velocity (PV) rather than on which road it was travelling, thus opposing the right of way for vehicles on the main road. The velocity of this vehicle was then adjusted generating a gap enabling it to merge without collision at junction.

Building on the pro-active merging strategies [174], proactive sliding-windows approach [175] was presented for a junction on a highway with a ramp. Here the algorithm was designed to sequence all the vehicles in a pre-defined window range in the order of their merger at the junction. The velocity of these vehicles were then adjusted such that they merge appropriately. A different variation of similar approach was work on by paper [176] and an optimal merge sequence algorithm was developed for group of vehicles from two roads using the in-advance information on vehicles positions and velocities. Then the vehicles adjust their speeds to generate adaptive gaps to maintain the merge sequence.

Optimal scheduling of AV at intersections was studied using Mixed Integer Liner Program (MILP) [177]. Here, an intersection controller residing on a server was utilised to which on-coming connected AV were subscribed with time of entry, access and exit at cross-roads and based on this information the flow of vehicles encouraged into platoons to allow collision-free passage. Another decentralised Optimal Dynamic Rescheduling algorithm [178] was proposed to improve travel time and energy utilisation of CAV vehicles when approaching a 4-way signal-free traffic intersection.

In a separate study [179] deep reinforcement learning methods were uses to coordinate the lane merges for CAV, where the vehicles trajectory was determined using centralised *Traffic Orchestrator* model, data fusion, image recognition systems and V2X gateway. A study was conducted using Reinforcement Leaning approach [180] to optimise merge control and speed harmonisation for mixed traffic scenarios involving CAV on a highway lane closure using Q-network model.

The optimal vehicle coordination problem was addressed [181] for cross-road intersections with multiple road merges using centralised collision-free traffic scheduling framework solving non-convex coordination problem.

The cooperative speed harmonizing technique was studies to optimise road usage and lowering $CO_2$ emissions [182] using only the centralised approach, assuming no V2V communications. Here the vehicle travelling to separate roads were visualised as connected to two waves travelling towards an intersection based on a function and half a wavelength difference was formulated for waves from two roads leading into the intersection ensuring vehicles pass the intersection without any conflicts.

This is similar to the approach defined in this paper but differs significantly. In the previous paper vehicles only a single type of vehicle, *Car*, was referred and does not mentioned mixed length traffic. Using this as a basis, half a wavelength phase shift was sufficient to achieve the desired results. This would also only work, without affecting speeds of following traffic, if the front of vehicles travelling on main and slip roads are equidistant from the junction. This simulation step is not a true representative of real-world where road is shared by varying types of vehicles with mixed length ranges. Also, they could be anywhere positioned with respect to each other on two separate roads. In this paper, all of the above are considered and only certain vehicles are phase shifted which would approach the junction simultaneously. Other vehicles, given travelling at same speed would already be phase shifted and merge at junction uninterruptedly. Given the similarities between the two approaches, my model, mentioned in this chapter, is compared against the results from this study [182], to highlight the *effect-size* between the two models.

Although these studies provide a systematic merging algorithm to coordinate the flow of vehicles at a junction, all of the studies did not specify for when and for how long the speeds should be modulated. How the length of sliding window or group of cars conditions were determined. The studies the only considers cars in evaluations and did not mention mixed length traffic scenarios to realistically match real-world road traffic. Considering varying vehicle length is crucial in determining which vehicle should be slowed down for how long to avoid unnecessarily prolonged speed modulations. The methods also does not consider the effects of speed adjustments on following vehicles leading to *"slinky-type effect"* [183].

To the best of authors knowledge, the proposed method of traffic merging using destructive interference is not analysed in a mixed vehicle setup for congestion control.

## 5.2. Trial and Error

The dynamic gap generation model described in Section Chapter 4  worked by modulating the speeds of three vehicle categories, namely, *preceding*, *following* and the *convoy*, to generation a desired gap i.e. the tunnel's length, between the *convoy* and its *preceding* and *following* vehicles to enabled *convoys* travel via the tunnel in isolation. This idea of generating gaps between the groups of vehicles, if applied to the junction, could help in collision avoidance at junctions and controlling congestion. The approach is to create alternating equidistant gap blocks, one empty and one with vehicles, on two merging roads (*Main Road* and *Slip Road*), respective, such that at the junction, the vehicle block on the one road occupies the empty gap block on another. In order to achieve this, the desired empty gap block length was assumed to be the length of 50 meters (i.e. up to a platoon of five, 5 meters cars with 5 meters headway), followed by the equidistant vehicles block and so on.

But as the approach was studied and simulated, certain concerns with the method were highlighted. One of the major issues was with the generation of equidistant alternating blocks of vehicles and empty gaps. The time it took to slow down individual vehicles, as calculated using (10), from the given geo-reference location ($rP_{primary}$) positioned from the junction, as calculated using (12), to generate an empty gap block of 50 meters, the build-up of slowing *following* vehicles would be greater than 50 meters, resulting in shorter empty gap block but longer vehicular blocks, failing the merge sequence at the junction. As an example, to generate an empty gap block of 50 meters with *preceding* vehicles travelling at 50mph and *following* vehicles slowed down to 40mph, it would take ~14 seconds (including deceleration time), during which the *following* vehicles have had travelled ~254 meters before resetting their speeds to 50mph and be *preceding* vehicles for next empty block, thus rendering the approach unworkable.

The approach also considered to modulate the speeds of *preceding* and *following* vehicles as blanket over *n* number of identified vehicles, rather than individual vehicles reducing speeds as they cross $rP_{primary}$. The intention was, as a group of vehicles, suitably calculated to generate vehicular and empty gap blocks, were slowed, and sped up, then the build-up would be kept to minimum, potentially achieving equidistant gaps. The blanket speed change approach did help in minimising the build but not enough to generate 50 meters equidistant gap blocks.

The approach of dynamic gap generation model deemed suitable under a scenario where desired gaps between the *convoy* and its *preceding* and *following* vehicles were generated once or after a considerable delay, like in a tunnel scenario where the two DGVs *convoys* could be time to arrive at the tunnel following the success passage of the first one, which could be say after 15 minutes the passage of first *convoy*.

It was determined to successfully enable the collision avoidance by modulating the speeds of the vehicles, the approach would work if individual vehicles are monitored and adjusted. Section 5.3 details the methodology of destructive traffic-wave interface approach for collision avoidance at the motorway junction.

## 5.3. Final Solution & Methodology

The main objective of the study is to avoid congestion and to help enable uninterrupted merging at a motorway junction for all the AV vehicles travelling from a *Slip Road* to a *Main Road*. Two roads define a set $B = \{Main, Slip\}$. The proposed approach is inspired from noise cancellation technique which utilises the destructive wave interference mechanism [184]. The mixed flow of traffic involving automated *Cars* and *Heavy Good Vehicles (HGVs)* of varying lengths on the main and slip roads are visualised as traffic waves show in Figure 67. As measured from a fixed position on the road, in traffic flow terms, the *amplitude* is 1 when vehicle is present else 0; the *pulse width* is the length of a vehicle; and the *one wave cycle* is the *pulse width* plus distance between two vehicles, which should at least be minimum safety distance.

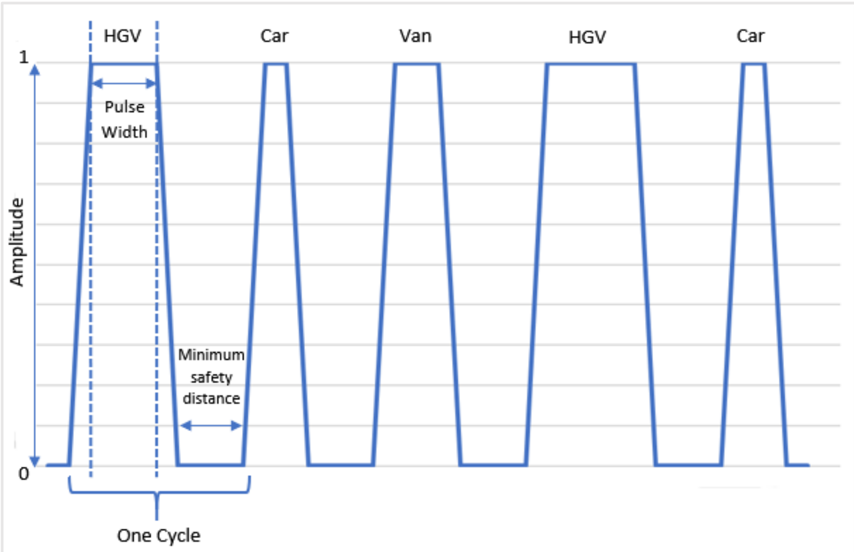

*Figure 67 Visual representation of traffic flow as a waveform*

The proposed method utilises the behaviour of AV vehicles whereby their flow could be controlled precisely. The study assumes that all the traffic would be autonomous, and the vehicles would maintain fixed safety distance $d_{safe}$ harmonising the flow. The method primarily uses a centralised approach to control the speed variations of the vehicles, assuming V2I communications are adequately established and speed updates during the phase-shifting procedure are relayed using DENM [145] or similar protocols. This is because V2V would not be effective for varying demographic conditions and for distance required to make necessary speed adjustments between two roads approaching a junction. Although V2V communication could be used in relaying the information to approaching vehicles about their phase shift and modified merge sequence.

In the real-world traffic flow scenario, on motorways different mandatory speed limits are applied for different vehicle types, such as *Cars* at 70mph and *HGVs* at 60mph [185]. Thus, it becomes difficult to accurately phase shift the vehicles travelling on separate roads due to constant change in their positions with respect to each other. Also, the slow-down of a vehicle could affect the faster moving following vehicle. To cope with this problem, at a fixed equidistance from junction on *Main Road* and *Slip Road*, two checkpoints $d_{cp}$ for $b \in B$ are calculated as,

$$d_{cp} = (v \times t) + \delta \quad (34)$$

where $v$= phase shift velocity, $t$ = deceleration time and $\delta$ = C-ITS comms latency. The detailed formulation of the (34) is mentioned in the paper.

Another location $d_{reduceSpeed}$ is identified upstream from $d_{cp}$ for $b \in B$, where the speed limit for all the vehicles is reduced to a minimum mandatory speed limit $min(v_{mandate})$. This way all the AV would be travelling at a fixed position and distance from other vehicles on respective roads from this point onwards until reduced speed limit is reset after crossing the junction. The $d_{reduceSpeed}$ is calculated as,

$$d^{b}_{reduceSpeed} = d_{cp} - \left(d^{b}_{\vec{a}} + \varepsilon\right) \quad (35)$$

where $\varepsilon$ = safety constant to ensure all the vehicles have reduced before reaching $d_{cp}$ location, and $d_{\vec{a}}$ = distance taken to decelerate from maximum mandatory speed to minimum mandatory speed set at *d*, is calculated as,

$$d_{\vec{a}} = \left(\frac{(v_f - v_i)}{\bar{a}}\right) \times v_f \quad (36)$$

where $d_{\vec{a}}$ = deceleration distance, $v_i$= initial velocity, $v_f$= final velocity and $\bar{a}$ = average deceleration.

When the front of a vehicle $V_b$ for $b \in B$ travelling either on *Main Road* or *Slip Road* reaches the checkpoint $d_{cp}$, a geo-position check is performed on the alternate road to determine the presence of vehicles, either geo-positioned alongside or behind of $V_b$, within a geo-fenced distance $\lambda$ calculated as,

$$\lambda = L_b + \min(d_{safe}) \quad (37)$$

where *L* = length of $V_b$ calculated from its front, $d_{safe}$= safety distance between two vehicles, and $\min(d_{safe})$ = minimum safe distance as, 5$\leq d_{ange} < d_{safe}$ (in meters, and at least one average car gap i.e. 5m). This condition is important because when the vehicle is slowed down for phase shifting, it ensures that this vehicle's deceleration does not decelerate its following vehicle on slip road to adjust for $d_{safe}$, avoiding *"slinky-type effect"*.

If no vehicle is present within the $d_{range}$ on the alternate road then the phase shifting is not required, and this vehicle would merge at junction uninterruptedly and at a safe distance.

Else, the phase shifting would be required to generate a safe minimum gap between the merging vehicles at the junction.

To correctly phase shift, first it is important determined which vehicle would be slowed down in order to generate a desired minimum gap safely and optimally. The selection of this vehicle, either on main road or slip road, is dependent on the positioning of the vehicles with respect to each other within $d_{range}$. The conditions are identified, and appropriate rules are applied to determine desired vehicle as:

- If same length vehicles and their front positions are at their respective $d_{cp}$ locations at the same time, then select either of the two vehicles as desired vehicle
- If different length vehicles but their front positions are at their respective $d_{cp}$ locations at the same time, then select the vehicle with longer length as desired vehicles because it would require less time to travel the distance $\lambda$ for $L_b$of shorter vehicle.
- If the vehicle on one road is behind the other, then this is the vehicle, irrespective of their lengths.

Once the desired vehicle is identified, it would be reduced subtracting constant speed $c$ from the preceding vehicle's speed. A check for the speed of its preceding vehicle would be required, as it could be the case that the preceding vehicle's speed is also reduced for phase shift.

Using (36) where the deceleration distance is calculated based on identified new reduced speed ($v_f$) and (37), the displacement distance $\Delta d$ for the vehicle is calculated as,

$$\Delta d = \lceil (\lambda - \theta) + 2d_{\vec{a}} \rceil \quad (38)$$

where $\lceil \cdot \rceil$ = ceil operator; $\theta$ = relative gap between the positions of vehicle at $d_{cp}$ and the desired vehicle to be slowed down; and deceleration is multiplied by two as vehicle would slow down during phase shift and when at the junction, under normal traffic conditions. The relative gap $\theta$ is calculated as,

$$\theta = \left(P_{precedVeh} - P_{desiredVeh}\right) \quad (39)$$

where $P_{precedVeh}$= geo position at front of preceding vehicle

which was at $d_{cp}$, $P_{desiredVeh}$ = geo-position at front of desired vehicle to be slowed down. The gap between two vehicles would be calculated via haversine function [186-188].

Using (38), determine for how long the vehicle would be slowed down, referred to as speed reset time ($t_{reset}$) as,

$$t_{reset} = \left(\frac{\Delta d}{v_f}\right) + \delta \tag{40}$$

where $\delta$ = latency for C-ITS communications.

The new reduced speed ($v_f$) and speed reset time ($t_{reset}$) are then relayed to the desired vehicle using V2I communications immediately after the check and vehicle should start to slow down to achieve timely phase shift.

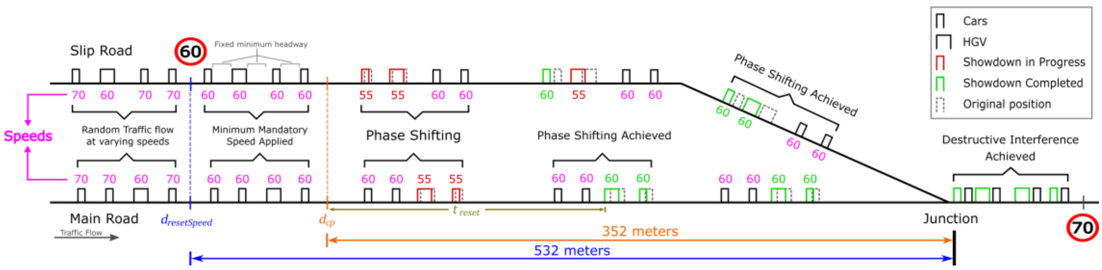


*Figure 68 Illustration of destructive traffic-wave interference model*

Figure 68 illustrates the detailed description of the methodology. It is important that $d_{cp}$ are positioned downstream from the junction at an equidistant to sufficiently allow the slowdown of vehicles within $t_{reset}$ duration for any length of vehicle. The longest vehicle length and its frequency could be determined from historic traffic data flow captured by DfT or Highways England in UK [105, 110].

## 5.4. Simulation Setup

To test the efficiency of proposed method and to optimise the merging of vehicles at a motorway junction using destructive interference, a traffic simulation software PTV Vissim version 2020 [189] was used. The simulations were performed on a single lane *Main Road* merging with a single lane *Slip Road* of exact lengths up to the junction. For this study PTV Vissim's COM interface [164] was used with Python scripting language version 3.7 to simulate and control the flow of autonomous vehicles and for implementing destructive interference between the vehicles. Two vehicles categories, *Cars* and *HGVs*, were simulated as fully connected and autonomous vehicles with their driving behaviour defined using Wiedemann 99 [93] the CoEXist [80] driving models. Table 42 defines the simulation and driving parameters for phase shifting of AV.

Table 42 PTV Vissim simulation parameters for simulating destructive interference using AV.

| **Parameters** | **Main Road and Slip Road** |
|---|---|

| | *Cars* | *HGVs* |
|---|---|---|
| Average desired deceleration | -2.75m/s$^2$ | -1.25m/s$^2$ |
| Vehicle length range | 3.5 – 4.5m | 10 – 12m |
| Wiedemann 99 CC1 (headway time) | 1s | |
| Look ahead distance (min) | 10m | |
| Look ahead distance (max) | 10m | |
| $d_{safe}$ | 17m | |
| $min(d_{safe})$ | 5m | |
| $d_{resetSpeed}$ | 532m | |
| $d_{cp}$ | 352m | |
| Safety constant ($\varepsilon$) | 10m | |
| Comms Latency (δ) | 100ms | |
| $min(v_{mandate})$ | 60mph | |
| Constant speed ($c$) | 5mph | |
| Autonomous driving - Enforce absolute braking distance | True | |
| Comms latency ($\delta$) | 100ms | |

The minimum and maximum values for '*Look ahead distance'* were set to ensure AV vehicles were able to drive with reduced headway of 10 meters without deceleration. This maximum headway value was determined based on real-world multiple-vehicle platoon trials conducted by SARTRE (Safe Road Trains for the Environment) project where vehicles were driven at 90km/h (56mph) with a gap of 6 meters between vehicles [190]. Using COM interface, the flow of vehicles was controlled so that it could accurately analysed which vehicles would be slowed down, and which would pass without applying the phase shift. The vehicles were continuously added by randomly selecting *Cars* and *HGVs* vehicle category, at two seconds interval, on both *Main Road* and *Slip Road* simultaneously. The initial speeds set for *Cars* and *HGVs* categories were 70mph and 60mph, respectively. To mimic the real-world flow, the positions of simultaneously added vehicles were offset randomly between 1m and 20m from the front of newly added main road vehicle, such they were not always positioned at exact same distance from the junction. This would lead to only certain vehicles being phase shifted i.e. vehicles within $\lambda$ distance. The $\lambda$ is dynamically calculated by the code based on equation (37).

The distances for $d_{reduceSpeed}$ and $d_{cp}$ were identified to ensure, first, the speeds of two maximum length *HGVs* vehicles travelling at equidistant from the junction from $d_{cp}$ locations, were successfully reduced from 60mph to 55mph, and second, phase shifting was successfully achieved between them before merging at junction with total phase shifted distance equals to 17m (12m + 5m).

To generate the benchmark measures and analyse the performance of the destructive interference model, the traffic flow is simulated as defined but with phase shifting logic disable via the code. The results are compared in two phases:

- *Phase I* – Merge sequence by comparing the traffic flow with and without the destructive interference model enabled.
- *Phase II* – Improvements in travel time, queue formations and traffic throughput, again by comparing the traffic flow with and without the destructive interference model enabled.

For *Phase II* additional setup was required. Three simulation scenarios were identified as:

- *Right of Way (ROW)* scenario, where traffic on main road have right of way over the vehicles coming from slip road.
- *No Right of Way (NROW)* scenario, where neither of vehicles have right of way and merge based on available gap at the junction.
- *Phase Shifted* scenario, where the destructive interference logic is applied via Python code.

To govern the traffic behaviour at the junction, *Conflict Area* component was used with settings as, '*Second link waits for First link'* for *ROW* scenario and *Undetermined'* for *NROW* and *Phase Shifted* scenarios, respectively.

For travel time and queue formation measurements, the simulation run was set to 180 seconds with traffic flow rate of ~1,800 vehicles per hour. This rate was chosen at it was observed to the average daily traffic flow on UK motorways [191]. The flow was measured at three seconds interval on *Main Road* and *Slip Road* which was then averaged over five random simulation runs using *'Random Seed'* simulation setting of PTV Vissim.

For the traffic throughput analysis, the simulation run was set to 630 seconds and the traffic volume was periodically increased every 90 seconds, by reducing the rate (frequency) at which they were added to the simulation, as shown in Table 43.

Table 43 Traffic volume increment at 90 seconds interval

| **Simulation Interval (s)** | **Frequency (s)** | **Total Traffic Volume (vehicles/hr)** |
|---|---|---|
| 0-90s | 6 | 1200 |
| 90-180s | 4 | 1800 |
| 180-270s | 3 | 2400 |

| | | |
|---|---|---|
| 270-360s | 2 | 3600 |
| 360-450s | 1.5 | 4800 |
| 450-540s | 1.2 | 6000 |
| 540-630s | 1 | 7200 |

The traffic volume in Table 43 was determined using the formulation as,

$$q = n \times \left(\frac{3600}{t}\right) \tag{41}$$

where *q* = vehicle flow per hour, *n* = number of vehicles travelling in *t* seconds (as measured from a fixed location) and *t* = time for passing vehicles in seconds. Here *n* is 2, one vehicle for each road section and *t* is the frequency.

## 5.5. Results

The results are detailed in three phases. The *Phase I* aims at verifying the destructive interference model approach in generating uninterrupted traffic merge at motorway junction dynamic gaps using PTV Vissim traffic simulation. In *Phase II*, the study analysis the impact of dynamic wave interference model on queue formation and travel time with a constant traffic flow, and effects of increase in gradual traffic throughput on queues. In *Phase III*, the travel time results from the study [182], are compared with the destructive interference model.

### 5.5.1. Phase I

To accurately analyse the implementation of the destructive interference model, the results were measured by comparing waveform captures of traffic flow from *Main Road* and S*lip Road* at the junction. The PTV Vissim's *Detector* component was used to capture the presence of vehicle on either of the roads by positioning one *Detector* for each road at same merge location. The *Conflict Area* at the junction was configured to be *Passive* to allow vehicles from *Slip Road* to merge, rather than waiting for a suitable gap on the *Main Road*. This is reflected in Figure 69 waveform capture where colliding vehicles are overlapped, which in real-world would lead to queue formations and congestion built-up. For the *Phase I*, the results are measured for 95 seconds simulation duration. The Figure 69 and Figure 70 show the capture staring from 30th second because it took ~35 seconds for first set of vehicles to arrive at the junction from the entry point i.e. 880m downstream. This was chosen to easily analyse and verify the waveform capture. From Figure 69 it was be observed that at multiple intervals the *Main Road* waveform overlapped the *Slip Road* waveform indicating that vehicles from these two roads arrived at the junction together.

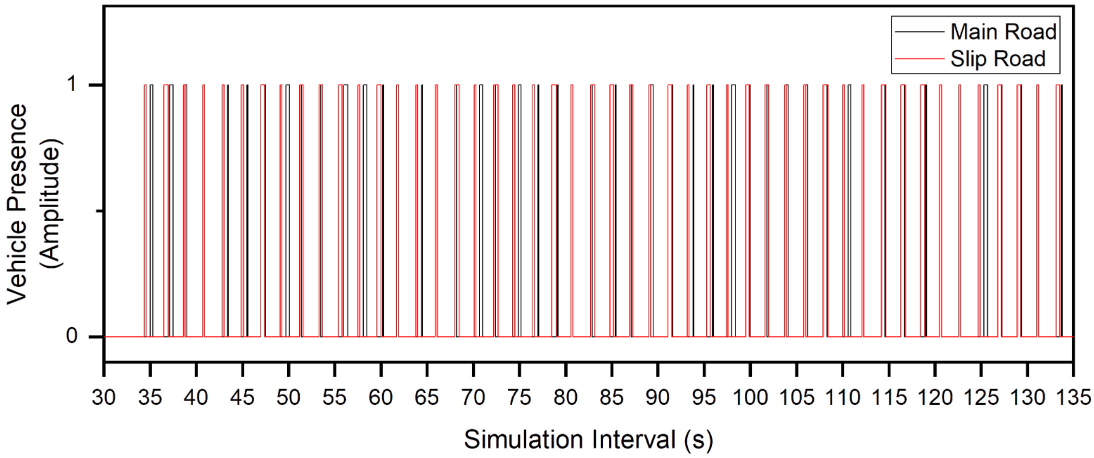


*Figure 69 Waveform capture with destructive interference disabled showing colliding vehicles.*

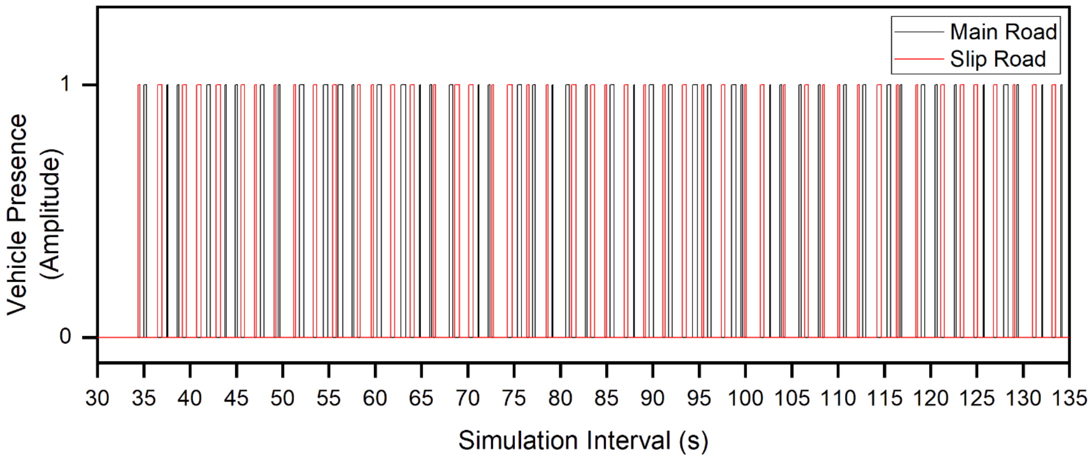


*Figure 70 Waveform capture with destructive interference enabled showing no colliding vehicles.*

Figure 70 showed the waveforms from *Main Road* and *Slip Road* for a simulation run with destructive interference implementation and for the same duration. It could be observed that none of the waveforms overlap each other when the phase shifting was applied to the vehicles within geo-fenced distance $\lambda$, and by reducing the speed from 60mph to 55mph for the vehicles that collided in Figure 69. This would refer to vehicles were able to merge at the junction in a sequential order, uninterrupted.

By analysing the *Phase I* results it could be stated that by phase shifting the only those AV which were within geo-fenced $\lambda$ distance, and with a small change in speed, i.e. from 60mph to 55mph, destructive traffic-wave interference was successfully achieved. The vehicles at the junction were able to merge in orderly manner with the minimum safe headway for autonomous vehicles without being stopped for another vehicle to pass. The model was able to phase shift multiple size vehicles randomly position on two roads, mimicking real-world road traffic scenarios.

## 5.5.2. Phase II

In this phase the results were measured and compared for queues built up, travel times and effects of increase in traffic throughput.

### 5.5.2.1. Queue Analysis

Figure 71 shows two graphs depicting the AMQL over the duration of the simulations. The top graph shows the queue built-up on main road for *NROW* scenario only. For the *ROW* scenario, as the *Main Road* has right of way, no queues were observed. For the *Phase Shifted* scenario, no queues were observed, and traffic was able to travel through the junction uninterrupted for the course of entire simulation.

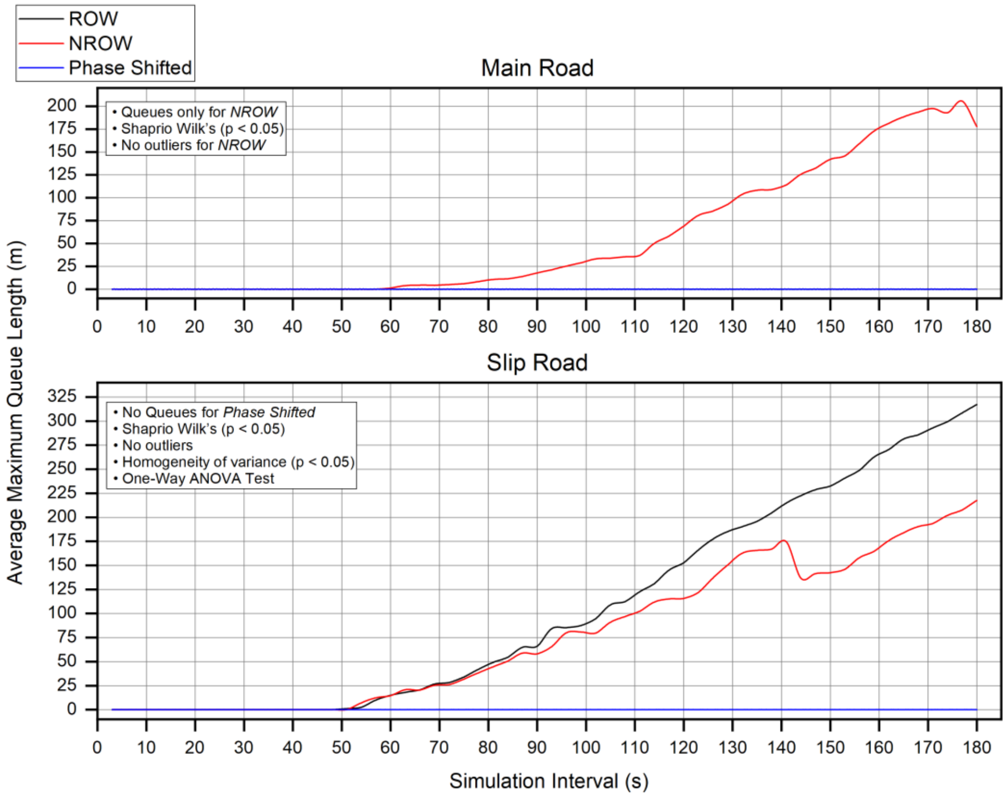


*Figure 71 AMQL formations on Main Road and Slip Road for three simulation scenarios.*

Analysing the first top graph for *Main Road*, it was noted that AMQL was only observed for *NROW* scenario and not for *ROW* and *Phase Shifted*. Also, the queues were significantly higher, with an average length of ~83 meters and maxing at ~206 meters before dropping.

By analysing the bottom graph for S*lip Road*, a One-Way ANOVA was conducted with Tukey HSD post-hoc testing to determine if AMQL were significantly different between *ROW* and

*NROW* scenarios. The AMQL decreased from *ROW* (*N* = 44, *M* = 145.01, *SD* = 100.16), to *NROW* (*N* = 43, *M* = 108.91, *SD* = 62.04), and to *Phase Shifted* (*N* = 46, *M* = 0.00, *SD* = 0.00), and AMQL was statistically significantly different between the three categories, $F(2, 130) = 55.93$, $p < 0.005$. Table 44 shows the post-hoc test results between scenarios.

Table 44 Multiple comparisons between scenarios using Tukey's post-hoc test

| **Dependent Variable: Slip Road AMQL** | | | | |
|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Sig.** | **95% Confidence Interval** | |
| | | | **Lower Bound** | **Upper Bound** |
| **ROW** | NROW | 0.038 | 1.61 | 70.60 |
| | Phase Shifted | 0.000 | 111.09 | 178.93 |
| **NROW** | ROW | 0.038 | -70.60 | -1.61 |
| | Phase Shifted | 0.000 | 74.79 | 143.03 |
| **Phase Shifted** | ROW | 0.000 | -178.93 | -111.09 |
| | NROW | 0.000 | -143.03 | -74.79 |

By further analysis, the maximum AMQL observed for the *ROW* was measured at ~317 seconds, in comparison to ~217 seconds for *NROW* i.e. a decrease of ~25% on *Slip Road*.

#### 5.5.2.2. Travel Time Analysis

Figure 72 shows two graphs analysing AVTT taken by vehicles to travel 0.71 miles distance from *Main Road* and *Slip Road* for three identified scenarios.

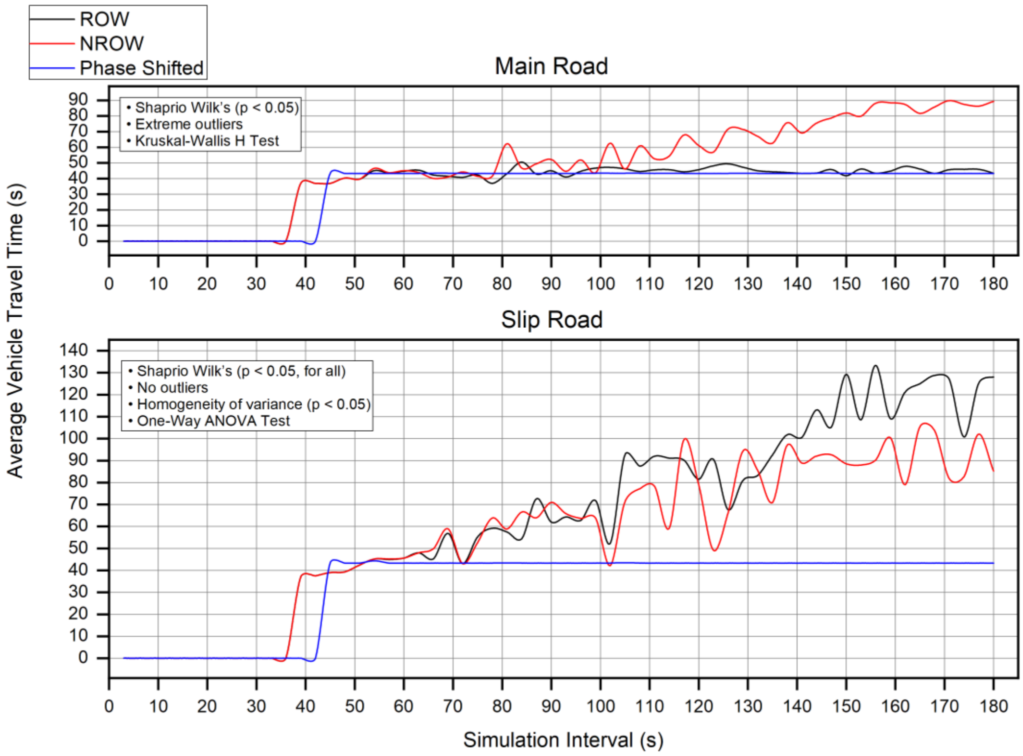


*Figure 72 AVTT for vehicles on Main Road and Slip Road for three simulation scenarios.*

Analysing the first top graph for *Main Road*, Kruskal-Wallis H was conducted to determine if there were differences in AVTT between scenarios. Distributions of AVTT scores were not similar for all scenarios, as assessed by visual inspection of a boxplot. AVTT reduced from the *NROW* (*N* = 48, *MR* = 98.13), to *ROW*(*N* = 48, *MR* = 66.80) to *Phase Shifted* (*N* = 46, *MR* = 48.62), and the ATD differences were not statistically significant, $\chi^2(2) = 35.54$, $p < 0.005$.

By further analysing the data, the maximum AVTT observed for the *NROW* was measured at ~90 seconds, in comparison to ~50 seconds for *ROW* and ~43 for *Phase Shifted* scenarios, i.e., a decrease of ~44% and ~52% respectively, on *Main Road*. Although, the AVTT between the *ROW* and *Phase Shifted* was mostly similar, AVTT decreased by ~14% for between the two, i.e. the gain of ~7 seconds for vehicles in *Phase Shifted* categories.

Analysing the second bottom graph for *Slip Road*, a Welch's One-Way ANOVA testing was performed with Games-Howell post-hoc testing. The AVTT decreased from *ROW* (*N* = 48, *M* = 80.04, *SD* = 30.53), to *NROW* (*N* = 48, *M* = 69.80, *SD* = 20.81), and to *Phase Shifted* (*N* = 46, *M* = 43.33, *SD* = 0.14), and AVTT was statistically significantly different between the three categories, Welch's $F(2, 62.67) = 72.74$, $p < 0.005$. Table 45 shows post-hoc test results between the scenarios.

Table 45 Multiple comparisons between scenarios using Games-Howell post-hoc test

| **Dependent Variable: Slip Road AVTT** |
|---|

| (I) Groups | (J) Groups | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|
| | | | Lower Bound | Upper Bound |
| **ROW** | NROW | 0.139 | -2.48 | 22.97 |
| | Phase Shifted | 0.000 | 26.04 | 47.38 |
| **NROW** | ROW | 0.139 | -22.97 | 2.48 |
| | Phase Shifted | 0.000 | 19.20 | 33.74 |
| **Phase Shifted** | ROW | 0.000 | -47.38 | -26.04 |
| | NROW | 0.000 | -33.74 | -19.20 |

By further analysis, the maximum AVTT observed for the *ROW* was measured at ~133 seconds, in comparison to ~105 seconds for *NROW* and ~44 for *Phase Shifted* scenarios, i.e. a decrease of ~7% and ~61% respectively, on *Slip Road*. The AVTT between the *ROW* and *NROW* was mostly similar, with a small gain in travel time of ~8 for *NROW*. When *ROW* and *NROW* were compared to *Phase Shifted* scenario, the vehicles gained ~69 seconds and ~61 seconds, respectively.

Another interesting note was, although for *ROW* and *NROW*, the AVTT measurements were statistically different for vehicles traveling on *Main Road* and *Slip Road*, for *Phase Shifted* scenario, due to uninterrupted flow, AVTT was not significantly different and travel time difference observed was ~1 second.

#### 5.5.2.3. Traffic Throughput Analysis

Figure 73 shows two graphs analysing the effect of periodic increase in traffic volume on queue formations for *ROW*, *NROW* and *Phase Shifted* scenarios on *Main Road* and *Slip Road* respectively.

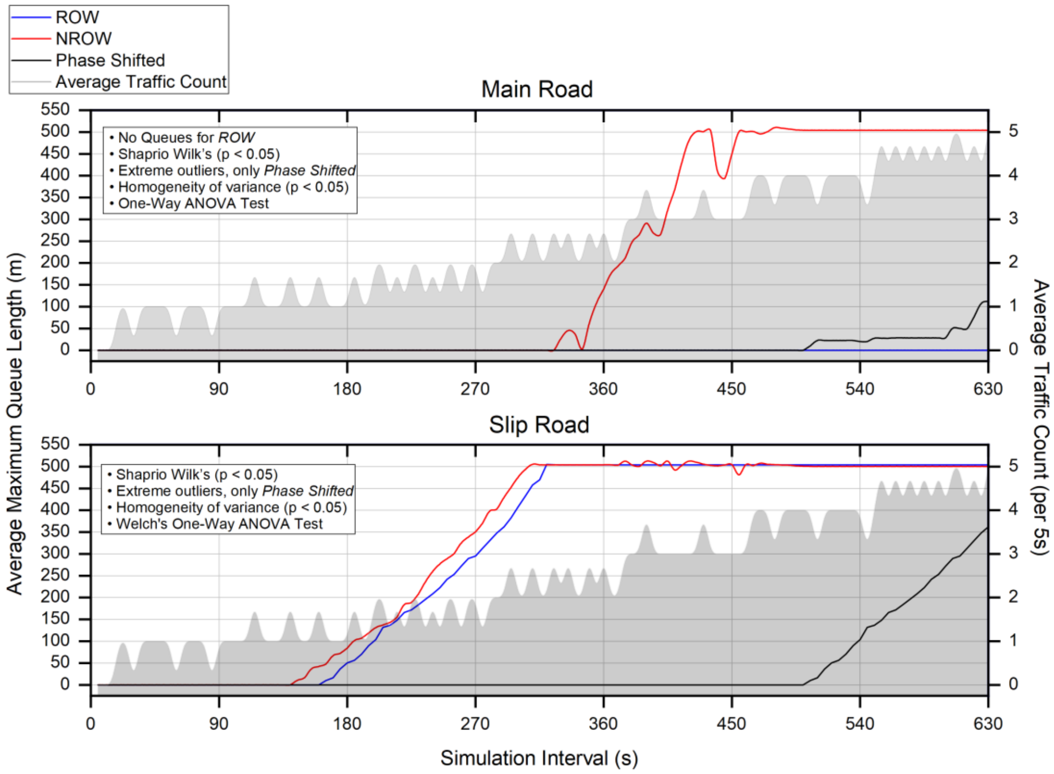


*Figure 73 AMQL analysis with increasing traffic throughput.*

Analysing the first top graph for Main *Road*, a One-Way ANOVA was conducted with Tukey HSD post-hoc testing to determine if AMQL were significantly different between the scenarios. The AMQL decreased from *NROW* (*N* = 126, *M* = 197.10, *SD* = 231.32), to *Phase Shifted* (*N* = 126, *M* = 7.43, *SD* = 18.51), and to *ROW* (*N* = 126, *M* = 0.00, *SD* = 0.00), and AMQL was statistically significantly different between the three categories, $F(2, 375) = 87.59$, $p <$ 0.005. The Tukey's post-hoc test results are highlighted in Table 46.

Table 46 Multiple comparisons between scenarios using Tukey's post-hoc test

| **Dependent Variable: Main Road AMQL** | | | | |
|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Sig.** | **95% Confidence Interval** | |
| | | | **Lower Bound** | **Upper Bound** |
| **ROW** | NROW | 0.000 | -236.82 | -157.38 |
| | Phase Shifted | **0.899** | -47.15 | 32.29 |
| **NROW** | ROW | 0.000 | 157.38 | 236.82 |
| | Phase Shifted | 0.000 | 149.94 | 229.38 |
| **Phase Shifted** | ROW | **0.899** | -32.29 | 47.15 |
| | NROW | 0.000 | -229.38 | -149.94 |

By further analysing *Main Road*, it was observed that for *ROW* scenario no traffic queues were formed as traffic continued to flow because of *'right of way'*. For the *NROW* scenario the queue formation started when the total traffic volume was ~3600 vehicles/hour or more with average queues of ~197 meters and maxing out when flow reached ~6,000 vehicles/hour on the *Main Road*. On the other hand, for the *Phase Shifted* scenario the queue formation begun significantly later than *NROW*, between 450-540s with the total traffic flow of 6, 000 vehicles/hr, with average queues of ~30 meters, and reaching the maximum of 112 meters at the end of simulation with 7,200 vehicles/hr traffic flow.

Analysing the second bottom graph for *Slip Road*, a Welch's One-Way ANOVA testing was performed with Games-Howell post-hoc testing. The AMQL decreased from *NROW* (*N* = 126, *M* = 316.69, *SD* = 220.12), to *ROW* (*N* = 126, *M* = 306.39, *SD* = 223.46), and to *Phase Shifted* (*N* = 126, *M* = 37.33, *SD* = 87.76), and AMQL was statistically significantly different between the three categories, Welch's $F(2, 207.25) = 146.36$, $p < 0.005$. The Games-Howell post-hoc tests are presented in Table 47.

**Table 47** Multiple comparison between scenarios using Games-Howell post-hoc test

| **Dependent Variable: Slip Road AMQL** | | | | |
|---|---|---|---|---|
| **(I) Groups** | **(J) Groups** | **Sig.** | **95% Confidence Interval** | |
| | | | **Lower Bound** | **Upper Bound** |
| **ROW** | NROW | **0.928** | -76.19 | 55.58 |
| | Phase Shifted | 0.000 | 218.47 | 319.65 |
| **NROW** | ROW | **0.928** | -55.58 | 76.19 |
| | Phase Shifted | 0.000 | 229.43 | 329.29 |
| **Phase Shifted** | ROW | 0.000 | -319.65 | -218.47 |
| | NROW | 0.000 | -329.29 | -229.43 |

By analysing traffic flow on the *Slip Road*, it was observed that queues were formed for all three scenarios. The queue formation begun for *ROW* and *NROW* between 90-180s interval with traffic flow of 1,800 vehicles/hr with an average length of ~306 meters and ~317meters, respectively. The queues for these two scenarios, on *Slip Road*, maxed out at ~500 meters, with the traffic flow of ~3,600 vehicles/hr. For *Phase Shifted* scenario the queue formation begun significantly later than other two scenarios, between 450-540s with the total traffic flow of 6,000 vehicles/hr, which continued to rise sharply with the increase in traffic flow.

It was observed from all the three measurements (AMQL, AVTT and Traffic Throughput Analysis), that irrespective of the scenarios (*ROW*, *NROW* and *Phase Shifted*), the traffic on *Slip Road* observed significant flow disruptions in compassion to the traffic on *Main Road.*

## 5.5.3. Phase III

In this phase the results were measured and compared for travel time analysis between the destructive interference model and Cooperative Speed Harmonization (CSH) model proposed in the study [182]. To accurately compare the *effect-size* between two models, the simulation behaviour mentioned in the Section 4.5 was modified mimic CSH model simulation conditions. The road layout was changed to include a 3-lane *Main Road* section with total driving distance of 7kms and a single lane *Slip Road* with total driving distance of 6.5kms. The simulation only uses cars vehicle type with all vehicles being simulated as *AV-Cars.* Table 48 details the simulation parameters for this specific simulation scenario.

**Table 48** Traffic simulation parameters to match CSH simulation model

| Parameters | Value |
|---|---|
| Vehicle density | 100 vehicles/min |
| Traffic speed | 70mph |
| Traffic composition | All *AV-Cars* |

Remaining simulation parameters are unchanged and are as per Table 42. The destructive interference simulations were run for 10 times. The average travel times and standard deviations of the models are mentioned in Table 49.

**Table 49** CSH and Destructive Interference model results

| Parameters | CSH model | Destructive Interference model |
|---|---|---|
| Average Travel Time | 294s | ~224s |
| Standard Deviation | 0.36 | 0.57 |

The *effect-size* between the two models is calculated using *Cohen's d* [192].

$$Cohen's\ d = \frac{|M_{CHS} - M_{DI}|}{SD_{pooled}} \tag{42}$$

where, $M_{CHS}$ = average travel time of control CSH model, $M_{DI}$ = AVTT of destructive interference (DI) model, $SD_{pooled}$ = pooled standard deviation calculated as,

$$\sqrt{\frac{\left(SD_{CHS}{}^{2} + SD_{DI}{}^{2}\right)}{2}} \tag{43}$$

where, $SD_{CHS}$ = standard deviation of CSH model, $SD_{DI}$ = standard deviation of destructive interference model.

Using (42), the effect-size calculate was equal at 146.84. This indicates the large *"effect-size"*, meaning the destructive interference has the larger effect on improving travel times between the two models. AVTT with destructive interference model improved by ~27%.

## 5.6. Conclusions

By analysing the *Phase I* results it could be stated that by phase shifting only those AVs which were within geo-fenced $\lambda$ distance, and with a small change in speed, i.e. from 60mph to 55mph, destructive traffic-wave interference was successfully achieved. The vehicles at the junction were able to merge in orderly manner with the minimum safe headway for autonomous vehicles without being stopped for another vehicle to pass. The model was able to phase shift multiple size vehicles randomly positioned on two roads, mimicking real-world road traffic scenarios.

By analysing the *Phase II* results, it was observed that *Phase Shifted* scenario outperformed the *ROW* and *NROW* traffic scenarios in terms of queue formations, travel time and traffic throughput. For queue and travel time analysis, it was noted that with exact same simulation parameters and traffic flow but change in *Conflict Area* setup, significantly different results were observed between the scenarios. As expected, *ROW* scenarios lead to higher traffic built up on *Slip Road* and travel time than for vehicles on *Main Road*. Also, measuring the performance between *ROW* and *Phase Shifted* scenarios, especially for vehicles on *Main Road*, *Phase Shifted* scenario performed better than *ROW* potentially due less *'jerky'* movement of vehicles at the junction to accommodate merging traffic. For the *NROW* scenario, statistically similar performance was observed for *Main Road* and *Slip Road* traffic. This was due to fact that neither of road had right of way. The *Phase Shift* scenario showed significant improvements by completely eliminating queue formations and reduction in average travel times by ~31% and ~41% for *ROW* and *NROW* scenarios, respectively.

For the traffic throughput analysis, it was interesting to note that the *Phase Shifted* scenario was able to cope with ~50% and ~108% higher traffic throughput than *ROW* and *NROW* scenarios for *Main Road* and *Slip Road* respectively. It was observed that *Phase Shifted* scenario was affected due to the lack of headway required for phase shifting due to increase in traffic which was nearly equivalent to 4-lane traffic flow on a merging a single lane traffic.

The novel destructive traffic-wave interference model proves to be an effective and efficient way in improving traffic merging at junctions and in reducing congestion. This would be particularly useful in scenarios where the expansion of roads is not possible or difficult due to physical or monetary aspects. The results showed that proposed model of is effective and efficient in improving travel times, queues and congestion, as compared to existing flow patterns with right of way rules implemented on most of the motorway. Using the proposed destructive interference model, it would be possible to accommodate more AV vehicles on per lane basis without causing queue build-ups.

It is interesting to note that using the proposed method, the speed modulation is only required for certain vehicles which are travelling within geo-fenced distance of each other. By modulating the speed only by small value and for shorter duration to generate minimum safety gap between the two vehicles, the impact on neighbouring traffic was observed not to be significant. The overall phase shifting event lasted for ~8 seconds and for 534 meters.

Having said that, the proposed model is only suitable for traffic with fully autonomous vehicles or with vehicles with very high connectivity. For the conventional driving vehicles involving a human driver, the model will not be compatible as it would require precision driving and control of vehicles as promised by autonomous vehicles at higher speeds. Also, the model would work most efficiently in free flow traffic state, avoiding congestion and would not be a resolution to already congested road network.

The proposed method is applied to AVs driving individually and not as part of platoon. Future work should expand the destructive interference model to carter multi-vehicle platoon trains along with the performance analysis of the model in urban areas with multiple close distance junctions and roundabouts, to improve road traffic problems.

# Chapter 6

# Discussion

The primary objective of this research was to improve the movement of road freight approaching a tunnel by developing novel solutions utilised by connected freight vehicle alongside intelligent infrastructure. The thesis detailed the fulfilment of the objective and the simulated positive impact on road tunnel traffic.

## 6.1. Reflections and Impacts of Research

Chapter 3 was able to identify the concerns with semi-automated implementation of check and allow procedures at the Dartford Crossing tunnel. Since the toll booths were removed from the tunnel in 2016, significant traffic improvements were observed with the use semi-automated tunnel with sensors and detectors. But still the full potential of the tunnel traffic flow was not achieved. Now, the tunnel closures have been reduced to ~4 hours of unplanned closures per day involving extractions, escorts and missed detects, in comparison traffic being stopped all the time at the tolls. But still, the tunnel is only able to cope with ~3,500 vehicles/hour which is nearly half of the optimal flow capacity on a 4-lane road, as per the case study [104].

It was also noted that due to a large number of freight vehicles travelling through the tunnel, ~4 DGVs/AVLs escorts were required per hour, lasting ~90 seconds, and releasing up to eight vehicles at a time into the empty tunnel to ensure safety of road users and tunnel infrastructure. Also, to ensure only compliant vehicles travel via the tunnel, detectors detects ~11 vehicles a day for extraction, which are then removed from the main road for inspection and in some cases fined. This again led to the closure of tunnel for up to ~3 minutes, with maximum observed for ~20 minutes. But sometimes due to errors on the part of the system, operators, or by the driver of non-compliant vehicle dodging the extractions and continue travel to the tunnel, which could in turn lead to an accident due to uncheck hazardous goods carried or inappropriate dimensions of the travelling vehicle.

Another major issue observed by analysing Dartford Crossing data was the *Self-declare* and inspection procedure at the KMA. All the DGVs traveling via the tunnel must report at KMA for inspection before travelling to the tunnel. As observed from the data, the majority of these vehicles were sent back to the A282 for usual travel via the tunnel which puts the additional strain on the near-by A206 roundabout and associated roads. Additionally, the inspection process could take up to 30 minutes to 8 hours in extreme case which could severely impact the supply chain and incur losses to businesses.

A traffic simulation model was developed using the PTV Vissim software which simulated the traffic at the Dartford Crossing tunnel and surrounding roads, based on the data obtained from Highways England. This included near realistic traffic composition, flow rate, traffic signal positioning and timings to ensure near realistic traffic model, which when analysed against real-world traffic data was statistically different (*p = 0.006)* but with the "*effect size*" of $\eta^2 = 0.23$, meaning the difference was very small.

The research presented the benefits of using CAV-F and how intelligent infrastructure could help with the verification of the carried goods and vehicle dimensions could be performed via C-ITS communication, prior to approaching the tunnel. This would help determine non-compliant vehicle and help the drivers to re-route to alternate roads, saving them time and money. The study simulated the scenarios where tunnel closures ranged from 9 closures per hour to zero closures, using the developed PTV Vissim model. The thesis draws the comparison for reducing closures counts between the real-world scenario with conventional vehicles (*Phase I*) and scenario where only the DGVs vehicles were replaced by CAV-F vehicle type, amidst conventional traffic (*Phase II*). The results were analysed to gauge reduction in traffic queues and travel time, and increase in traffic throughput.

The results showed that, for *Phase I*, reducing hourly closures to two or less made the statistically significant improvements in reducing the AMQL. It was interesting to note that in *Phase I* simulation, queues were observed on N06 road section, even with *Zero* closure scenario. This seemed to be the case because of DGVs and ALVs were still travelling to KMA and were joining the traffic on A282 via N06 slip. As noted in *Phase II* where CAV-F vehicles were simulated and *Self-Declared* vehicles were not travelling to KMA, the vehicle category benefited assumed C-ITS communication to ensure compliance. Although the queue was still developed on the N06 for *Zero* closure and three *AV* scenario, they were ~59% shorter than conventional closure scenarios in *Phase I*. This would indicate that the N06 queues were because of regular traffic on surrounding A206 roads rather than because of KMA. Another interesting driving behaviour was noted between the *AV-Cautious*, *AV-Normal* and *AV-Aggressive* scenarios, where vehicles simulated with *AV-Normal* driving behaviour performed better than the other two, improving queue by ~23% overall. The *AV-Aggressive* scenarios performed the worst amongst three and the reason for this could be disproportionately low traffic count of CAV-F vehicles in comparison to surrounding conventional vehicles for *AV-Aggressive* and sensitive driving parameters setup for near perfect simulation of fully autonomous vehicles.

Analysis of AVTT showed that for *Phase I* with the reduction in closure counts below two, the AVTT for *Self-Declared*, *Undeclared* and *Missed Detect* vehicle category reduced significantly between the closure but were still significantly higher than *Cars*, *HGVs* and *Buses* vehicle categories, by ~71%, due to their closure events. Furthermore, the travel time for *Self-Declared* to be *Released* was captured to be the longest, which in real-world would be greater still than what's been reported from simulation results and Dartford Crossing data analysis. This is due to uncaptured duration spent by drivers waiting to be escorted parked following the checking at the KMA, as the vehicles are usually escorted in convoys of up to 9 vehicles at a time to optimise the *Release*. Again, *Phase II* showed the benefits of using CAV-F and avoidance of KMA for inspection, where the AVTT for CAV-F vehicles and for all three driving behaviours were statistically similar to *Cars*, *HGVs* and *Buses* vehicle categories. The *Self-Declared* noted the improvement of ~18 minutes, whereas *Undeclared* and *Missed Detect* vehicles' AVTT improved by ~8 minutes.

When the traffic throughput impact was analysed, for the simulation scenario where all the freight vehicles travelling at the Dartford Crossing tunnel were simulated as CAV-F, results supported the hypothesis and the reduction in headway, standstill distance and increase in scope of connectivity did help improve the traffic throughput. Using *Mod2* driving behaviour the Dartford Crossing road infrastructure would be able to support up to 7,000 vehicles/hr with ~500 m average queues. It was noted that with AMQL ranging between ~100m to ~2kms, the total average travel time for all different traffic flows is just under 3 minutes, which is approximately the average travel time for ~4 km (2.5 mi) A282 road section towards Dartford Crossing tunnel at 80 km/h (50 mph). This could imply that although the longer queues are formed, they are cleared quickly not leading to prolonged congestion and with shorter headway, standstill distance and scope of connected vehicles, traffic was able to travel faster. In contrast, though the increase in speed limit was observed to be productive, the impact on CAV-F vehicle category was not productive.

As a progression from Chapter 3 Chapter 4 introduced the novel mathematical model developed with objectives to:

- Automate the escorting procedures at the tunnel.

- Enable platooning of hazardous goods vehicles in a safe and secure manner.

The Dynamic Gap Generation model showed that by appropriately changing and resetting the vehicles' speeds at appropriate locations, vehicular gap could be generated which in turn help in isolated travel of the convoy of DGVs via the tunnel in an efficient manner. As the desired safety gaps were formed between the DGVs *convoy* and its *preceding* and *following* vehicles, platooning of connected and autonomous DGVs could be possible, which in case of an accident would be far apart from other road traffic. This research ensured nearly all possible road layouts approaching a tunnel were applicable to the model and thus six traffic scenarios were identified ranging from single lane with single mandatory speed and single convoy scenario to multi-lane with multi mandatory speed limit and multiple separate convoys on each road sections. The study also considered the tunnel's length in determining desired vehicular gaps and determined that for any tunnel longer than 3kms, the desire gap should not be the length of the tunnel but a pre-determined safety distance to ensure safe passage of the convoy.

The simulations were performed to verify:

- The effectiveness of the mathematical model in improving overall traffic flow.
- That the calculated $rP$ and $rP_{reset}$ locations were appropriately placed for the dynamic generation of desired gaps such that the *convoy* could travel via the tunnel in isolation or with sufficient gaps.

New traffic simulations were developed for each of the identified road layouts. The results were compared against the simulation mimicking Dartford Crossing tunnel's escorting procedure, as analysed in Chapter 3 using conventional vehicle based on Wiedemann driving model only. The results measured the increase in traffic density and reduction in travel time and traffic queues when the Dynamic Gap Generation was enabled.

The results in the *Phase I – Visual Inspection Analysis* showed that the formulation developed for all different road layouts for the placement of $rP$ and $rP_{reset}$ locations worked as expected in generating the dynamic gaps suitably enough to allow safe passage of the DGVs *convoy* via the tunnel and without too much gap between *preceding* and *following* vehicles, optimising the flow.

The results in *Phase II* showed that the traffic density was statistically different for categories with gap generation enabled (*Mixed Traffic* and *CAV*) in comparison to *Baseline* conventional escorting procedure. This was specifically true for scenarios with single convoys irrespective of single or multi road layouts. The main differences were observed was that for the conventional escorting procedure the traffic continued to flow at a near stable rate until the escort even when the tunnel was in closure for ~180 seconds. During this, the traffic started to build significantly and took considerable amount of time to normalise, ~150 seconds on average. Whereas for the simulation with dynamic gap generation enabled, irrespective of *Mixed Traffic* or all *CAV* simulation, the traffic flow behaved comparatively stable throughout the simulation, where traffic density only increased during active gap generation between vehicles which was normalised in ~90 seconds on average. On the other hand, for simulation road layout scenarios with multiple road and multiple convoys, the ATD measurements were statistically very similar, albeit *Baseline* simulations still look longer time to normalise traffic following the closures in comparison to other two simulation categories with dynamic gap generation enabled.

Analysing the results for AVTT, it was noted for the *Baseline* due to tunnel closures the travel time varied significantly during the simulation. Due to closure, the congestion caused led to nearly twice the travel time in free flow state for nearly all road layout scenarios. This increase was directly proportional to the closure duration of the tunnel, longer the closure longer the travel delays. For other two simulation categories, *Mixed Traffic* and *CAV*, the AVTT appeared to be stable throughout the simulation, except during the middle of simulation when speeds were slowed down to generate dynamic gaps. But as the modulated speeds were reverted to original mandatory speed limits at appropriate $rP_{reset}$ locations, the impact of reduction in speed was minimised. It was also noted that the time taken to plateau the increase in AVTT for all *CAV* scenarios was ~48% less than that of *Baseline*.

When queue analyse was performed, for the single lane road layout scenarios, the AMQL appeared to be similar for all three simulation categories, only rising significantly higher for *Baseline* during the tunnel closure event. But for the layouts with multiple roads, the queue patters appears to be very different, depending on the road section. For all the three categories, no queues were observed on the *First Slip* for any of the road layouts, being farthest from the tunnel. On *Main Road* and all multiple road layout scenarios, the queues for *Baseline* scenario were significantly higher than the other two categories. For comparison for *Baseline* category, the queues kept rising for most of simulation due to closure event and peaked at 300 to 400 meters, only to plummet after the tunnel reopens for all traffic. In contrast, the queues for other *Mixed Traffic* and/or *CAV* categories were observed during the gap generation, peaking at 10 to 50 meters at maximum. Finally, on *Second Slip* being the closest to the tunnel, saw the surge in traffic queues for all three categories, specifically for a scenario with single convoy travelling on a multiple road layout but with single mandatory speed limits. For other multiple road layout scenario, the queues were significantly higher for *Baseline* category but not for other two. That means the queues on *Second Slip* for *Baseline* category were always rising following the closure of the tunnel but for dynamic gap generation model scenario negligible queues were observed for all except single convoy with single mandatory speed. The reasons for this could be first, spread of one large convoy with smaller convoys on all roads which would require comparatively shorter duration on each of the road sections to generate desired gaps before the speeds being reset; and secondly, multiple mandatory speed limits in decreasing order as approaching the tunnel. This seems to help dampen the impact of speed changes for gap generation by gradual but regular drop in speeds for *preceding, convoy* and *following* vehicles.

Overall, by analysing all three result measures, it was noted that significant traffic flow improvements were observed via the simulations, when Dynamic Gap Generation model was enabled.

Finally, moving on the last question of research, where the aim was to generalise the gap generation model and outside the scope of tunnel infrastructure. Using the approach of vehicular gaps between the vehicles, the objective was to reduce queue formations and collision avoidance at motorway junctions. Initially the detailed gap generation model in Chapter 4 was tried to generate alternating vehicular gaps of 50 meters, interleaved with equidistant slots of 3-5 vehicles, depending on vehicles length and safety distance. But this approach did not prove useful due to "*slink-type effect"*, where the duration for which vehicles were slowed down to generate 50 meters gaps, in that duration the pile up of slow following vehicles was more than 50 meters, never giving an opportunity to form a train of alternating equidistant gap and vehicle slots. To improve the gap generation, blanket speed reduction and reset was tested to achieve alternating equidistant gap and vehicle slots, but this approach also did not work in achieving desired results. Finally, the novel destructive traffic-wave interreference model was developed, whereby potential colliding vehicles travelling on separate roads, approaching a junction, were slowed down or *phase shifted* such that they merge at the traffic uninterrupted.

The simulation models were developed to test the developed formulation. The results were compared between the scenario simulating autonomous vehicles (as per CoEXist driving model) with wave interference model disabled and other with wave interference model enabled. To effectively realise the benefits of the formulation autonomous *Cars* and *HGVs* vehicles were necessary, as the proposed model requires fine control on the movement of traffic which is possible using non-human driven vehicles. The objective was to ensure that using the wave interference model, collision avoidance could be achieved with gradually increasing traffic density, as would happen in real-world motorways in mornings and evenings. Three scenarios were determined, *Right of Way* (ROW), *No Right of Way* (NROW) and *Phase Shifted*. The results were then measured for reduction in queues and travel time and increase in traffic throughput.

In *Phase I* results, the measurements showed that when the wave interference model enabled, vehicles did not overlap at the junction by phase shifted vehicles using a small reduction in speed of 5mph i.e. from 60mph to 55mph, proving its correct formulation.

By analysing the *Phase II* results, it was observed that *Phase Shifted* scenario outperformed the *ROW* and *NROW* traffic scenarios in terms of queue formations, travel time and traffic throughput. For queue and travel time analysis, it was noted that with exact same simulation parameters and traffic flow but change in *Conflict Area* setup, significantly different results were observed between the scenarios. As expected, *ROW* scenario lead to higher traffic built up on *Slip Road* and travel time than for vehicles on *Main Road*. Also, measuring the performance between *ROW* and *Phase Shifted* scenarios, especially for vehicles on *Main Road*, *Phase Shifted* scenario performed better than *ROW* potentially due less *'jerky'* movement of vehicles at the junction to accommodate merging traffic. For the *NROW* scenario, statistically similar performance was observed for *Main Road* and *Slip Road* traffic. This was due to fact that neither of road had right of way. The *Phase Shift* scenario showed significant improvements by completely eliminating queue formations and reduction in average travel times by ~31% and ~41% for *ROW* and *NROW* scenarios, respectively. For the traffic throughput analysis, it was interesting to note that *Phase Shifted* scenario was able to cope with ~50% and ~108% higher traffic throughput than *ROW* and *NROW* scenarios for *Main Road* and *Slip Road* respectively. It was observed that *Phase Shifted* scenario was affected due to the lack of headway required for phase shifting due to increase in traffic which was nearly equivalent to 4-lane traffic flow on a merging a single lane traffic. As it was observed the phase shifting procedure lasted for ~8 seconds and for ~500 meters, and even with a flow of ~1,800 vehicles/hour, the slowdown of vehicles did not cause traffic disruptions.

## 6.2. Limitations and Future Works

The scope of this research was to analyse real-world traffic flow data, identify the capabilities of CAV-F amongst conventional traffic and develop mathematical models to improve the movement of CAV-F vehicles and the connectivity element of CAV in terms of C-ITS protocols and implementations was outside the scope of study. The research results were limited to the simulated environment, which was developed based on real-world data and was proven to be near realistic for Dartford Crossing tunnel analysis. Future works should try and implement the developed novel mathematical models in real world to test and verify their effectiveness with connected vehicle in CAV testbeds or open roads. Future studies could expand the simulation models to simulate complex traffic conditions involving planned or unplanned incidents to study the behaviour of CAV-F and verification of models.

The future work may focus on analysing the impacts of increased traffic on emissions and fuel consumption. The optimisation of routes and driving pattern for CAV over a longer road network should be considered to determine the cost benefits for freight supply chain.

Having said so, the proposed model would struggle for vehicles with human drivers requiring higher speed tolerances (the current UK acceptable tolerance is 10%+2mph), which is difficult to control given randomness of speed variations. Until stringent speed control measures using speed cameras, law enforcement measures and using connected services such as VSPD are applied, the model would render unsuitable for conventional vehicles. The model would be best suited for the traffic conditions where majority of vehicles are connected or automated.

The current model is limited to identification of $rP$ locations and is unable to determining of safety distances required between the *preceding*, *convoy* and *following* vehicle groups. This would be specifically applicable for longer tunnels greater than 3km where complete isolated travel would be impracticable and costly. It is also limited in accurately identifying speed reset locations ($rP_{reset}$) for larger road networks with longer tunnels and should be investigated in future works.

Future works should also include the investigation of proposed mathematical model in improving motorway and urban road network in easing congestion an alternative to existing ramp metering techniques.

# Chapter 7

# Conclusions

The findings and conclusions presented in this thesis are summarised in this chapter. From the literature review in Chapter 1 and 2 the four research questions were identified and were addressed in the thesis. In order to improve the road traffic movements (especially for freight), the following conclusions were reached from the study:

- Reduction in escort/extraction tunnel closure to two or less per hour led to significant traffic flow improvements, for conventional hazardous vehicles in current real-world scenario with no connected vehicles or intelligent tunnel infrastructure.
- When the CAV-F vehicles are used instead of conventional HGVs in an intelligent tunnel infrastructure framework, significant traffic improvements were realised and a tunnel was able to support higher than anticipated vehicles volume.
- CAV-F can help automate escort procedures by dynamically modulating traffic speeds at correct locations, enabling safe movement hazardous goods via tunnel.
- CAV can help improve traffic at motorway junctions by collision avoidance and uninterrupted traffic merging by modulating vehicles' speeds dynamically to phase shift each other approach to junction.

In Chapter 3 the positive results from the near realistic traffic simulation model highlighted the advantages of CAV-F. It was interesting to see that by only replacing conventional DGVs and ALVs categories to CAV-F, significant improvements were achieved in reducing the travel time and road traffic queues, although the aggressive implementation of CAV-F was rather counterproductive. Thus, a careful approach will be required in determining the driving parameters according to traffic conditions and road infrastructure to make the best use of CAV-F technology. The study also emphasised on the importance of C-ITS technology and showed that if valid V2I communications are established, they could help reduce or eliminate the requirement of tunnel closures for check and allow procedures. This could in-turn benefit the supply chain for freight and haulier companies by increasing their productivity and turnaround time. This advocates the case for CAV and showcase the opportunities for government and local councils to invest in enabling the road tunnel infrastructures with the C-ITS technologies, and for freight vehicle manufactures and logistic partners in intelligence vehicular technologies. The benefits would not be limited to traffic flow improvements but will also help enable safer and secure transit. So, to summarise:

- Significant improvements are observed for travel time and traffic queues with small penetration of CAV-F alongside conventional vehicles.
- Results for aggressive driving behaviour for CAV-F are not productive and thus autonomous driving parameters for CAV-F are required to be fine-tuned.
- Importance of proactive intelligent communications is highlighted, especially for hazardous goods vehicles approaching a tunnel to verify tunnel compliance.

The use of connected DGVs have been studied in the past and the Stockholm Bypass tunnel is actively incorporating intelligent infrastructure to help safe and secure movements in the tunnel. But none yet focused on determining where would be the optimal positioning of C-ITS system to help improve the flow. The novel mathematical model was developed to provide formulation to calculate optimal geo-referenced location for C-ITS communication. This would enable an effective and efficient way to escort DGVs and similar vehicles such as Abnormal Load Vehicles (ALVs) requiring safe and secure passage via a road tunnel. With the help of dynamically generated convoy of DGVs platoons, the need of check and allow procedures would be eliminated at the tunnel improving flow conditions and in turn benefit environment with potentially reduced congestion. This would also be particularly useful for DGVs in real-world scenario to benefit from platooning as they could be safer and efficient to travel as a group. This is currently a concern as in case of an incident involving a DGVs platoon could be fatal or have significant harmful impact of traffic and road infrastructure, especially in a road tunnel [193]. But if the *convoy* is isolated for a relatively short period of time and with appropriate safe buffer gaps between its neighbouring vehicles, the benefits of DGVs platooning could be realised. By merging more *convoys* together, especially for the individual vehicles travelling on slip roads, would help escort more vehicles through the tunnel. Overall, this advocated the necessity of upgrading the exiting tunnel infrastructure and to consider the inclusion of C-ITS technology from early stages of new tunnel development, increasing the socio-economic benefits to tunnels surroundings and also to freight industry by improving and optimising their supply chain.

Lastly, with the generalisation of the developed mathematical model, the benefits of connected and autonomous vehicles were also realised on general motorway junctions. The novel destructive traffic-wave interference model proved to be an effective way of collision avoidance and to increase the traffic throughput by enabling uninterrupted flow of vehicles.

The benefits of the approach were that the implementation only focused on vehicles that were deemed to be approaching at the tunnel simultaneously, which would be a small comparatively small percentage of vehicles as a whole. Also, it required subtle speed variation to enable successful phase shifting. The simplicity of the approach would mean that the solution could be tried and tested in AV test beds with comparative easy to other collision avoidance methods.

To summarise, this research was successful in achieving all its objectives. Using the real-world data, a near realistic traffic simulation model was developed which was able to understand the problem areas and provided insight on how small procedural changes in existing tunnel procedures could lead to significant traffic flow and operating cost benefits. The research was able to support the use of CAV-F vehicles in improving tunnel traffic. This research also contributed to effectively enhance the movement of traffic in tunnels and motorways by developing two novel mathematical solutions, which proved their effectiveness via traffic simulation models, using CAV.

# Appendix I

The Table 50 shows the per minute averaged travel time values across the three MIDAS locations (M25/4059, M25/4054 and M25/4054) and six hour readings (0000hrs on 03rd May 2017, 0600hrs on 15th November 2017, 0900hrs on 18th December 2017, 1400hrs on 26th January 2018, 1600hrs on 01st February 2018 and 1800hrs on 07th March 2017) for real-world and simulated model as match for above locations and dates.

**Table 50** Averaged real-world and simulation model travel time observations

| Observation resolution (*n)* minute | Averaged Real-World Travel Time (s) | Averaged Simulated Travel Time (s) |
|---|---|---|
| **0** | 59 | 58 |
| **1** | 60 | 59 |
| **2** | 62 | 56 |
| **3** | 60 | 55 |
| **4** | 64 | 56 |
| **5** | 65 | 58 |
| **6** | 66 | 60 |
| **7** | 61 | 61 |
| **8** | 63 | 60 |
| **9** | 64 | 61 |
| **10** | 57 | 59 |
| **11** | 64 | 59 |
| **12** | 60 | 62 |
| **13** | 61 | 57 |
| **14** | 55 | 57 |
| **15** | 46 | 60 |
| **16** | 48 | 58 |
| **17** | 46 | 57 |
| **18** | 44 | 58 |
| **19** | 49 | 57 |
| **20** | 58 | 59 |
| **21** | 57 | 57 |
| **22** | 61 | 59 |
| **23** | 64 | 57 |
| **24** | 65 | 59 |
| **25** | 65 | 59 |
| **26** | 66 | 57 |
| **27** | 69 | 54 |
| **28** | 64 | 58 |
| **29** | 66 | 58 |
| **30** | 64 | 60 |
| **31** | 68 | 61 |

| | | |
|---|---|---|
| **32** | 70 | 61 |
| **33** | 64 | 61 |
| **34** | 65 | 59 |
| **35** | 63 | 61 |
| **36** | 61 | 61 |
| **37** | 64 | 57 |
| **38** | 62 | 58 |
| **39** | 60 | 56 |
| **40** | 62 | 59 |
| **41** | 56 | 60 |
| **42** | 56 | 59 |
| **43** | 57 | 58 |
| **44** | 63 | 58 |
| **45** | 66 | 57 |
| **46** | 58 | 57 |
| **47** | 59 | 57 |
| **48** | 65 | 58 |
| **49** | 62 | 58 |
| **50** | 62 | 62 |
| **51** | 62 | 60 |
| **52** | 61 | 61 |
| **53** | 62 | 63 |
| **54** | 60 | 64 |
| **55** | 57 | 59 |
| **56** | 54 | 60 |
| **57** | 52 | 61 |
| **58** | 56 | 60 |
| **59** | 52 | 60 |

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