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Traffic simulation of connected and autonomous freight vehicles (CAV-F) using a data-driven traffic model of a real-world road tunnel

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ABSTRACT

The study is based on the Dartford-Thurrock Crossing tunnel, Kent, UK. It analyses the impact of the tunnel closures necessary for monitoring the flow of Dangerous Goods Vehicles and Abnormal Load Vehicles as per The European Agreement concerning the International Carriage of Dangerous Goods by Road regulations. A traffic simulation model is developed using PTV Vissim software, based on real-world Dartford Crossing traffic data and validated against independent Motorway Incident Detection and Automatic Signalling data. The autonomous driving implementations of Dangerous Goods Vehicles and Abnormal Load Vehicles, defined as per CoEXist project in the PTV Vissim software, are compared against the conventional vehicles traffic simulations. The results show that if the tunnel closures are reduced to two or less per hour then significant improvements in road congestion and travel time are observed. Furthermore, the benefits of autonomous Dangerous Goods Vehicles and Abnormal Load Vehicles are observed in improving traffic queues and travel times, given that the Dartford Crossing tunnel is appropriately equipped with intelligent communication technologies. The study shows that even with a small proportion of Connected and Autonomous Vehicles, the movement of road traffic can largely be influenced.

1. Introduction

The road freight transportation is one of the major indicators of the country's growth and economic development. The movement of freight is directly proportional to the variations of global economic markets. This correlation can be clearly observed with an increase in freight transportation prior to the global recession of 2008, a decline during the recession, and followed by a gradual increase after the recovery [1]. Due to improvements to the international trade regulations to increase the efficiency of the freight industry supply chain, the Average Daily Traffic (ADT) of freight vehicles is on the rise [2]. It is no surprise that freight transportation is identified as one of the major contributors of traffic-related problems like congestion, road accidents, travel delays and air pollution [3].

Although, many different types of goods are carried by freight in this study, the focus is on the problems concerning the carriage of hazardous goods and abnormal loads especially through a road tunnel. The freight transport vehicles carrying hazardous goods such as flammable liquids, toxic materials, harmful pathogens, nuclear waste, etc. have additional concerns regarding the safe and secure transit through a road network. When carrying these hazardous goods via the road, freight transport has to comply with many strict rules and regulations such as, The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) [4]. These regulations detail the procedures and restrictions on dangerous goods, their consignment procedures and use of means of transportation on their international movement to avoid and/or reduce road fatalities involving accidents, terrorist attacks, Boiling Liquid Expanding Vapour Explosion (BLEVE) and tunnel fire scenarios.

To travel via a tunnel, Dangerous Good Vehicles (DGVs) require additional regulations and risk assessment checks before they can make a journey through a road tunnel network [5]. The reason for this complex process is the wide range of hazardous goods they can carry, which if not dealt with care, could lead to fatal results. As a reminder, the tragedies of 1999 in Mont Blanc [6] and Tauern [7] road tunnels, highlight the paramount importance of tunnel safety. Such incidents have, and can lead to high fatalities, damage to tunnel infrastructure, environment and long closures which could have significant socio-economic impacts [8].

To improve the handling and transportation of freight goods, methods such as traffic management and routing systems and Intelligent Transportation Systems (ITS) are implemented which have been proven successful in past. The study [9] on freight operations in urban environ-

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ment using macroscopic traffic model and microscopic freight delivery operations showed positive results in improving traffic but was lacking real-world data to improve accuracy. Another study showed that ITS at cargo ports have increased the efficiency and reduced the cost and time spent on management activities [10]. Although the ITS solutions at the cargo ports are static in nature and work as pre-programmed instructions in a controlled environment, the benefits of having an automated system cannot be ignored. The congestion scenarios for freight transportation which proposed a set period to deliver goods have also been studied. The study [11] analysed the '*Time-dependant Vehicle Routing Problem (TDVPR)*' to ease the congestion and produced a distance and travel time matrix. The research conducted by Csaba and David [12] aimed at understanding the overall risks and benefits of freight transportation system using a traffic model in urban areas. Cooperative and Intelligent Transportation Systems (C-ITS) have also been proposed to enhance tunnel safety [13,14]. The report of recommendation and strategies for Stockholm Bypass tunnel [14] mentions the use of C-ITS in improving emergency management, avoiding standstill vehicles and managing DGVs. The report highlights the importance of Vehicle-2-Vehicle (V2V) and Vehicle-2-Infrastructure (V2I) communication technologies such as Cellular networks or Dedicated Short-Range Communication (DSRC) based on 802.11p standards and how their use in Stockholm Bypass tunnel will ensure road safety. A separate study on freight management using C-ITS [15] in urban areas also highlights similar improvements and benefits of using V2V and V2I. By implementing a coordinated, smart and intelligent road infrastructure, vehicles could be informed in advance of on-coming tunnel restrictions and would plan the journey accordingly. Prioritised dynamic lanes for DGVs, platooning, dangerous good carriage monitoring, etc. are also some of the examples which can benefit from the cooperative communication in improving the traffic flow.

Although previous studies have discussed potential solutions from which the flow and management of DGV and ALV will improve, they fail to address the impact of smart communications on road network alongside conventional traffic. The transition from current road traffic to fully connected and autonomous traffic will take many years and will be a step-wise change. However, the first generations of Connected and Autonomous Vehicles (CAV) and smart infrastructure examples have started to emerge in the real-world. It is now imperative to understand the effects of changes proposed by cooperative and smart transportation systems. The study will aim to analyse the influence of DGVs and ALVs on road traffic and how the introduction of small percentage of Connected and Autonomous Freight Vehicles (CAV-F) vehicles can change the dynamics of traffic flow, congestion and travel times for all the road users.

2. Methodology

The two objectives of this research are,

- Identify the existing impact of DGVs and ALVs on the traffic queues and travel delays near a road tunnel.
- Analyse the improvement impact of CAV-F implementations of DGV and ALV on tunnel but keeping other traffic as conventional.

This study proposes a hypothesis that by reducing or eliminating the tunnel closures required to govern the flow of DGVs and ALVs, using CAV-F, would improve the traffic queues and travel time without a need of infrastructure expansion. To support the hypothesis, the research has identified the Dartford-Thurrock River Crossing tunnel, UK (referred as '*Dartford Crossing*' in this paper) and the real-world data, between 1st March 2017 and 15th February 2018, is obtained from Highways England for the study. The tunnel is two bored, named West (4.8meters high) and East (5.0meters high), passing under the river Thames. The study only considers normal traffic flow conditions for traffic simulations. It analyses the unplanned tunnel closures pertaining to DGV and ALV at Dartford Crossing, defined as '*Release*' or '*Extraction*' closure events. It will not account planned closures for maintenance purposes and any accidents, planned/unplanned incidents or events are not examined.

The tunnel is classified as category C tunnel as per ADR regulations which does not allow vehicles with carriage exceeding total net explosive mass of 5000 kgs per transport unit. Additionally, there are other specific operating restrictions [16] relating to the passage of DGVs. All the DGVs are required to declare themselves at the designated area named Kent Marshalling Area (KMA), by exiting the A282 motorway at Junction 1A (J1A) (except for permitted vehicles as per ADR category C). The goods carriage and dimensions of the vehicles are checked and then the vehicle is either allowed to pass through a tunnel; escorted through a tunnel as a platoon in isolation of normal road traffic; or sent through an alternative route. The study defines these vehicles as '*Self-Declared*'. The escort procedure is defined as '*Release*' closure event and is only applicable to this vehicle category. It is important to note that in real-world Release event could escort up to nine vehicles at a time, but as the study is only interested in tunnel closure impact on the traffic flow, the event is modelled to represents one vehicle per *Release* event for Average Annual Hourly (AAH) duration, calculated by averaging all real-world *Releases* in the data.

Further restrictions apply to the physical dimensions of the vehicles [16]. Any vehicle up to the height of 4.8 m can use either bores but vehicle between 4.8 m and 5.0 m high must travel through the East Bore and vehicle taller than 5.0 m must exit A282 and navigate through an alternative route. To ensure only compliant vehicles enter the tunnel, the entrance of the tunnel is equipped with sensors which continuously monitors and record the road traffic activity on per millisecond basis. When a non-compliant is detected, the sensors are triggered, and the traffic signals and associated barriers are closed. The vehicle is then *Extracted* from the A282 road and navigated to the KMA for inspection. For the research, non-complaint vehicles are defined as '*Undeclared*' vehicles. When an *Undeclared* vehicle fails to extract due to human or system error and enters the tunnel, they are classified as '*Missed-Detect*'. The closure event associated to the extraction of *Undeclared* or *Missed-Detect* vehicle is defined as '*Extraction*' closure event. The duration of the events is calculated as AAH for identified *Extraction* and *Missed-Detect* events. To understand the impacts of CAV-F on the traffic flow at Dartford Crossing, the traffic simulation model is designed using the mentioned description of the tunnel.

2.1. Simulation model

The traffic simulation software PTV Vissim version 11 [17] is used in the research to model the Dartford Crossing traffic flow and comparing the existing conventional vehicles with simulated CAV-F vehicles, as in Fig 1.

The Vissim simulation is chosen because of an ability to simulate car-following behaviour with a stochastic element between different simulations to mimic real world scenarios. The model used is based on the Wiedemann [18] car-following model which considers the traffic flow patterns and analysis of congestion waves caused by lane changing, merging, and check & allow procedures. Using the PTV Vissim traffic modelling software, the Dartford Crossing road and infrastructure layout is replicated to represent the real-world traffic flow at the tunnel. The model will try and predict the traffic improvements with the introduction of autonomous variants of Self-Declared, Undeclared and Missed-Detect vehicles in easing traffic-related problems by simulating independent tunnel closure and autonomous vehicle (AV) driving scenarios [19].

The model also comprises of seven vehicle detectors. Four detectors on the A282 West and East bore are placed at the distance of 265 m, as per actual distance to the nearest gantry (4045B) from traffic signals on A282. They are configured to trigger on *Undeclared* vehicles and *Missed-Detect* vehicle categories to mimic the two *Extraction* events. The three separate detectors are placed on three FHB lanes and used to detect *Self-*

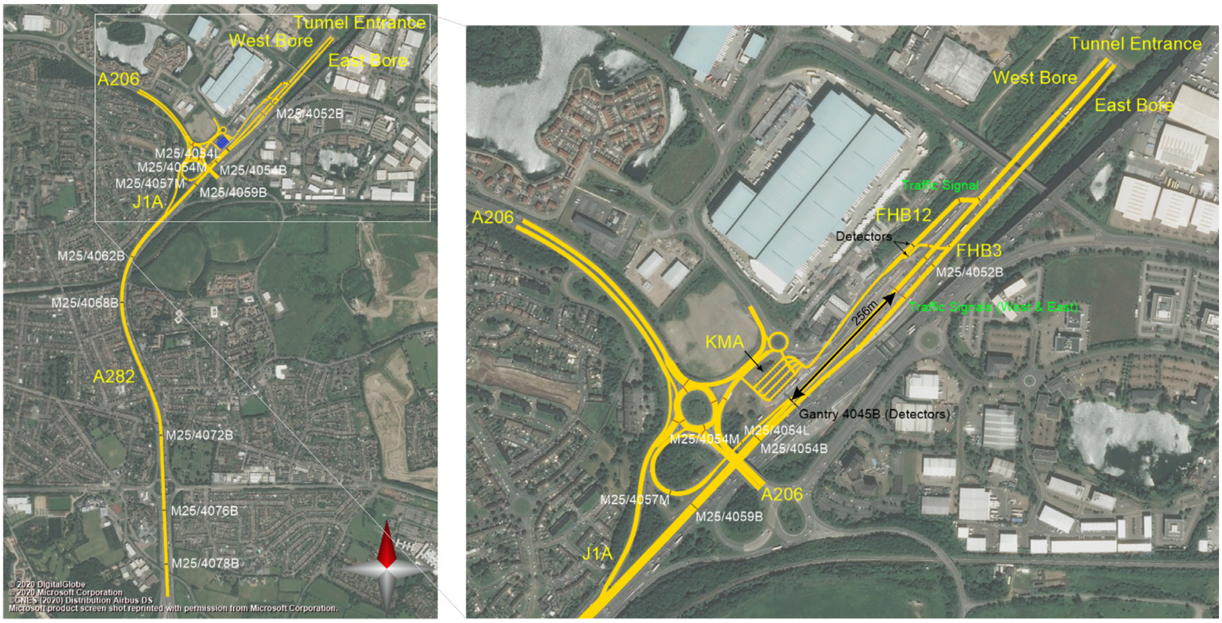

Fig. 1. PTV Vissim model highlighting key roads, detectors, and traffic signal locations at the Dartford Crossing.

Declared vehicles for Release events. The KMA is modelled as a parking lot where *Self-Declared* vehicles will be parked for AAH KMA duration before re-entering the simulation. The left-hand lanes of West and East bore tunnels, after J1A are modelled to accommodate freight vehicles only. Doing so will provide true travel delays of these vehicles. By modelling all the mentioned roads and traffic signal controllers leading to Dartford Crossing tunnel, the accurate impact of the traffic flow can be assessed. The traffic flow information for all road sections apart from J1A and A206 roads is obtained from Dartford Crossing data. Traffic flow on A206 road sections are approximated using traffic flow count obtained from DfT [20].

The traffic signals on the roundabout are modelled using the Fixed Time add-on module of PTV Vissim to mimic their real-world counterparts. The four traffic signals on A282 and two on FHB are implemented using the Time-dependant Vehicle Actuated Programming (VAP) add-on module of PTV Vissim. Using VAP, the change of traffic signals is programmed based on the detectors state. The traffic signals on A282 West and East bores are initialised to green and the traffic signals on FHB lanes are initialised to red traffic light state. This is the initial free-flow state of the model. On detection, VAP logic triggers a traffic signal change to red, referred as a closure, for the associated bore. If the detection is observed on the West bore then traffic signals for only this bore are set to red, but in case of East Bore detection, traffic signals on both bores are closed. Additionally, West Bore traffic signals are kept closed for an extra duration of 60 s than East bore. The timeout set for the traffic signal to go from red to green is calculated based on the formula:

$$t = d/(s - c) \tag{1}$$

where, t is the time to close traffic signals, in seconds, d is the distance between sensors and traffic signals (256 m), s is the current speed of detected vehicle in m/s (obtained from Vissim's detector object), and c is the signal transition time from red to green state, (set to 9 s, a sum of 6 s [transition between traffic signal states green-to-amber and amber-to-red] and 3 s, the correction for driving behaviour in PTV Vissim (based on trial-and-error).

Three detectors on the FHB are designed to trigger on *Self-Declared* vehicle category to mimic a Release event. On a detection, VAP logic prompts a traffic signal change to green for the associated FHB lane and the red for associated A282 traffic signals based on vehicle's destination, either to West or East bore. If the state of traffic signals on West or East bores is already red, then the predefined AAH release duration is added to the VAP's traffic state-change timer value. The logic for *Extraction* and *Release* closures are defined as functional specifications of the Dartford Crossing.

The KMA is modelled in Vissim as a parking lot to hold up 40 vehicles. The KMA have two exits. First exit leads to A206 and A282 roads and will be used by vehicle re-joining A282 to pass the tunnel or for vehicle who will be travelling via an alternative route. The second exit leads to three FHB lanes, used for escorting vehicles into the West and East bore. The vehicles at KMA will be parked for an average duration obtained from the data. The parked time will be added to the journey time of vehicles entering the KMA. The KMA vehicle flow is calibrated for frequency and composition of vehicles based on information obtained from the data.

The traffic model uses following input parameters for simulations, obtained from the Dartford Crossing data, as mentioned in Table 1.

The Vehicle Flow parameter is set for A282 entrance and A206 entrances. The Vehicle Flow Routing Percentage is set for each turn or junction to ensure correct number of vehicles travel through each road section in the network. Closure counts are controlled via the number of *Self-Declared* or *Undeclared vehicles*. For Closure and KMA Parking Durations the values are initialised in VAP module. Each simulation is configured to run for 4500 s and over ten random runs, based on random seed generator, set using general simulation parameters '*Random Seed*' [21].

2.2. 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 Motorway Incident Detection and Automatic Signalling (MIDAS) dataset [22,23], is conducted to ensure its validity. The average traffic flow per minute for hourly *Simulated and Real-world* groups is 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, 0000 hrs on 03rd May 2017, 0600 hrs on 15th November 2017,

Table 1
Input Parameters for simulating a traffic scenario at the Dartford Crossing tunnel.

Parameters	Description	Notes
Vehicle Flow	AAH traffic flow on A282 and KMA for Car, HGV and Bus vehicle categories.	Fixed for all scenarios.
Vehicle Flow Routing Percentage	AAH vehicle flow percentage per vehicle type, routing to and from A282, J1A, A206 and KMA road sections.	Fixed for all scenarios
Closure Counts	AAH counts of *Release*, *Extraction* and *Missed-Detect* closure events.	Differ between scenarios
Closure Durations	Annual Average Closure Duration (AACD) for *Release*, *Extraction* and *Miss-Detect* closure events.	Fixed for all scenarios
KMA Park Duration	Annual Average duration of *Self-Declared* vehicles in KMA for verification.	Fixed for all scenarios

0900 hrs on 18th December 2017, 1400 hrs on 26th January 2018, 1600 hrs on 01st February 2018 and 1800 hrs on 07th March 2017. The traffic flow from three specific MIDAS locations is observed. The locations are M25/4059B (GPS Ref: 555,823;174,985); M25/4054 L (West bore, GPS Ref: 555,952;175,143) & M25/4054B (East Bore, GPS Ref: 555,962;175,137); and M25/4052 L (GPS Ref: 556,202;175,425) & M25/4052B (GPS Ref: 556,217;175,412) [24]. 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)** [25] is calculated between *Real-World* and *Simulated* groups, and is subtracted from averaged simulated results. Relative difference **(d_r)** is calculated as:

$$d_r = |\Delta|/((x + y)/2) \tag{2}$$

where, $x = \sum_{i=0}^{n} \bar{x}_{real\text{-}world}$, $y = \sum_{i=0}^{n} \bar{y}_{simulated}$, $|\Delta| = |x - y|$. 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 2.

By further analysing histograms and box-plots, 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 [26] 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%.

2.3. Simulation steps

To test the two objectives of the research, the simulations 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 AAH 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 [19,27]. For the experiments the CAV-F vehicles are defined between three driving logics, as identified by CoEXist project. These are categorised as:

Table 2
Normality comparison AAH traffic flow.

Category	Shapiro-Wilk (α)	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

- *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.

As 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 [27]. 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 s applicable in *Phase II*)
- Undeclared closure duration = 187 s (not applicable in *Phase II*)
- Missed-Detect closure duration = 141 s (not application in *Phase II*)

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 s simulation run. To evaluate the results, two measures are identified.

2.3.1. 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:

$$Qbegin = v < 10\ mph, \tag{3}$$

$$Qend = v \geq 10\ mph, \tag{4}$$

Additionally, the vehicles on adjacent lanes are also considered. Four queue counters are positioned at one-metre distance before the four traffic signal heads on A282 West and East bores. The value of one metre is chosen to incorporate the Vissim's default standstill distance of 0.5 m 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.

2.3.2. Vehicle 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 M25/4052 L 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.

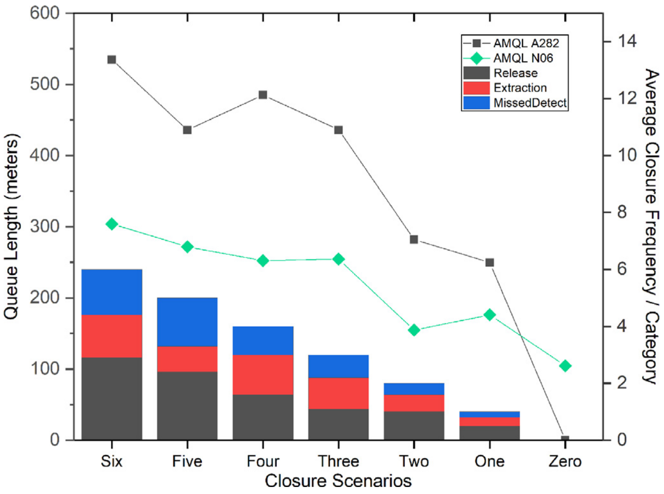

Fig. 2. Phase I Results - AMQL plot against varying scenarios.

3. Results

The results in both the phases are grouped for A282 and N06 Slip roads sections of Dartford Crossing.

3.1. Phase I – conventional vehicles

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

3.1.1. Queue length analysis

Fig 2 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 with the results shown in Table 3. 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.

A Kruskal-Wallis One-Way ANOVA [28] 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 lev-

Table 3
AMQL Normality Comparison A282.

Closure Scenarios	Shapiro-Wilk (α)	Skew	Skew Std. Error	Kurtosis	Kurtosis Std. Error
Six	0.010	0.653	0.309	0.146	0.608
Five	0.010	−0.672	0.309	0.380	0.608
Four	0.103	0.398	0.309	0.391	0.608
Three	<0.001	−0.938	0.309	0.489	0.608
Two	<0.001	0.181	0.309	−1.201	0.608
One	<0.001	0.499	0.309	−1.055	0.608
Zero	N/A	N/A	N/A	N/A	N/A

Table 4
AMQL normality comparison on N06.

Closure Scenarios	Shapiro-Wilk (α)	Skew	Skew Std. Error	Kurtosis	Kurtosis Std. Error
Six	<0.001	−0.557	0.309	−1.077	0.608
Five	<0.001	−0.377	0.309	−1.242	0.608
Four	0.005	−0.202	0.309	−1.265	0.608
Three	0.026	−0.250	0.309	−0.995	0.608
Two	0.025	0.684	0.309	0.494	0.608
One	<0.001	0.807	0.309	−0.507	0.608
Zero	0.053	0.505	0.309	0.340	0.608

els 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 [29]. Adjusted p-values are presented. This post hoc analysis revealed approximately statistically similar AMQL scores between the *One-Closure* scenario (*mean rank = 167.21*) and *Two-Closures* scenario (*mean rank = 180.30*) with $p > 0.05$ and between the groups of *Three-Closures* (*mean rank = 253.66*), *Four-Closures* (*mean rank = 263.12*), *Five-Closures* (*mean rank = 252.30*) and *Six-Closures* (*mean rank = 300.42*), $p > 0.05$. *0- Closure* scenario *(mean rank = 56.50)* was significantly different with all other scenarios ($p < 0.001$), along with all other combinations with *One-Closure* and *Two-Closures* scenarios ($p < 0.05$).

Similar statistical analysis was conducted for N06 Slip road section using the Shapiro-Wilk's test and results are shown in Table 4.

The $p > 0.05$ is only observed for Zero-Closure scenario and was normally distributed. The assumption of homogeneity was violated with $p < 0.001$ using Levene's test. Distributions of AMQL scores were not similar for all scenarios, as assessed by inspecting boxplots.

A Kruskal-Wallis One-Way ANOVA test showed that 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. The post hoc analysis revealed that the AMQL scores were approximately statistically similar between the *Zero-Closure* scenario (*mean rank = 73.13*) and *Two-Closures* scenario (*mean rank = 139.55*), with $p = 0.057$, between the *One-Closure* (*mean rank = 162.90*) and *Two-Closures* scenario, with $p = 1.000$, and between the *Three-Closures* (*mean rank = 256.56*), *Four-Closures* (*mean rank = 250.29*), *Five-Closures* (*mean rank =277.62*) and *Six-Closures* (*mean rank = 313.44*) scenarios with $p > 0.05$. For all other scenario combinations, the scores were statistically significantly different.

3.1.2. Vehicle travel time analysis

Fig. 3 shows the AVTT of six vehicles categories on per minute basis for each of the seven closure scenarios.

By statistically analysing the AVTT for different closure scenarios per category, using the Shapiro-Wilk's test, it was observed that for Car with $p < 0.05$ for all closure scenarios AVTT was not normally distributed. For HGV, Zero-Closure ($p = 0.481$, $n = 73$), Four-Closures ($p = 0.196$, $n = 73$) and Six-Closures ($p = 0.122$, $n = 73$) scenarios, the AVTT was approximately normally distributed but not for any other scenario ($p < 0.05$). For Bus, AVTT for all the scenarios was not normally distributed ($p < 0.001$). Travel time for Self-Declared vehicles was approximately normally distributed for all scenarios ($p > 0.05$). For Undeclared vehicles, travel time for Five-Closures scenario ($p = 0.107$, $n = 8$) was approximately normally distributed but not for any other scenarios ($p < 0.05$). And for Missed-Detect vehicles, AVTT for all the scenarios was not normally distributed ($p < 0.05$), apart from One-Closure ($p = 0.712$, $n = 3$), Two-Closures ($p = 0.114$, $n = 8$) and Three-Closures ($p = 0.803$, $n = 6$) scenarios. Table 5 details the test results for individual categories.

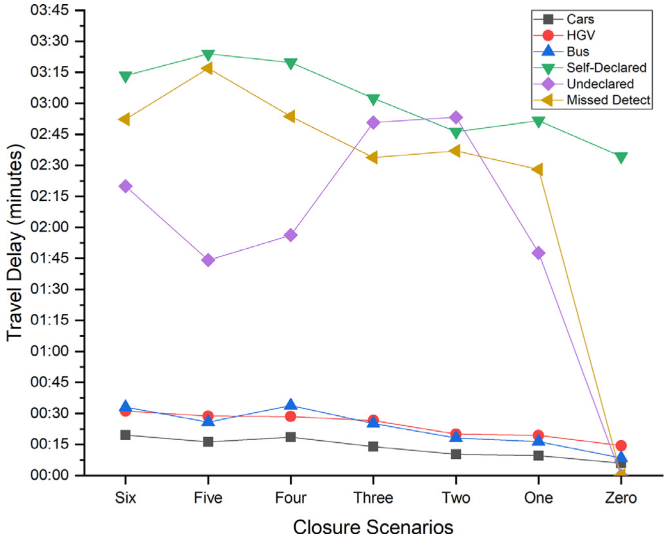

Fig. 3. Phase I Results - AVTT per vehicle categories against various scenarios.

Using the Levene's test, assumption of homogeneity was violated for *Car* ($p < 0.001$), *HGV* ($p < 0.001$) and *Bus* ($p < 0.05$) vehicle categories but was satisfied for *Self- Declared* ($p = 0.958$), *Undeclared* ($p = 0.316$) and *Missed-Detect* ($p = 0.339$) vehicle categories. By analysing the histogram, box plots and outliers for all the vehicle categories, the Kruskal-Wallis One-Way ANOVA test was identified for all vehicle categories except for *Self-Declared* vehicles, to examine statistical differences in the distribution of AVTT.

The *Undeclared* and *Missed-Detect* categories were analysed vehicle categories. Distributions of *Car, HGV* and *Bus* categories were approximately similar for all the scenarios, as assessed by visual inspection of a boxplot. Median AVTT scores were statistically significantly different between the closure scenarios for all three vehicle categories,

Table 5
Normality comparison of AVTT phase I.

Closure Scenarios	N	Shapiro-Wilk (α)	Skew	Skew Std. Err	Kurtosis	Kurtosis Std. Err
Car						
Six	74	0.029	0.778	0.279	1.226	0.552
Five	74	0.010	0.283	0.279	−0.454	0.552
Four	74	0.037	0.532	0.279	0.267	0.552
Three	74	<0.001	0.523	0.279	1.278	0.552
Two	74	<0.001	0.869	0.279	0.869	0.552
One	74	<0.001	0.361	0.279	1.855	0.552
Zero	74	<0.001	−5.149	0.279	37.837	0.552
HGV						
Six	73	0.122	0.373	0.281	0.010	0.555
Five	73	0.028	0.516	0.281	−0.341	0.555
Four	73	0.196	0.463	0.281	−0.241	0.555
Three	74	0.002	0.442	0.279	2.584	0.552
Two	73	0.002	0.532	0.281	−0.229	0.555
One	73	0.024	0.624	0.281	0.025	0.555
Zero	73	0.481	0.099	0.281	0.549	0.555
Bus						
Six	65	<0.001	2.719	0.297	8.775	0.586
Five	73	<0.001	2.553	0.281	7.022	0.555
Four	70	<0.001	5.805	0.287	40.730	0.556
Three	73	<0.001	3.099	0.295	12.059	0.582
Two	66	<0.001	4.103	0.289	21.048	0.570
One	69	<0.001	4.544	0.289	26.882	0.570
Zero	71	<0.001	1.977	0.285	5.060	0.563
Self-Declared						
Six	68	0.522	0.004	0.291	−0.607	0.574
Five	69	0.215	0.001	0.289	−0.734	0.570
Four	69	0.157	0.185	0.289	−0.611	0.570
Three	69	0.193	0.487	0.289	0.363	0.570
Two	69	0.138	0.220	0.289	−0.416	0.570
One	68	0.536	0.219	0.291	−0.520	0.574
Zero	69	0.269	−0.137	0.289	−0.763	0.570
Undeclared						
Six	14	0.032	−0.143	0.597	−1.681	1.154
Five	8	0.107	0.373	0.752	−1.745	1.481
Four	13	0.025	−0.404	0.616	−1.695	1.191
Three	11	0.001	−1.613	0.661	1.508	1.279
Two	10	0.009	−0.301	0.687	−1.985	1.334
One	7	0.005	−0.399	0.794	−2.705	1.587
Zero	0	N/A	N/A	N/A	N/A	N/A
Missed-Detect						
Six	14	0.003	1.249	0.597	0.105	1.154
Five	15	0.022	1.125	0.580	0.353	1.121
Four	10	<0.001	3.053	0.687	9.502	1.334
Three	6	0.803	0.834	0.845	0.695	1.741
Two	8	0.114	1.560	0.752	2.774	1.481
One	3	0.712	−0.757	1.225	–	–
Zero	0	N/A	N/A	N/A	N/A	N/A

Car ($\chi^2(6) = 122.975,\ p < 0.001,\ N = 518$); *HGV* ($\chi^2(6) = 100.743,\ p < 0.001,\ N = 512$) and *Bus* ($\chi^2(6) = 15.503,\ p = 0.017,\ N = 487$). Subsequently, pairwise comparisons were performed using Dunn's procedure. Adjusted p-values are presented. For *Cars,* the post hoc analysis revealed statistically significant differences in AVTT score between the *Zero-Closure* scenario (*Median (Mdn) = 126.00*) with all other scenarios ($p < 0.05$); and *One-Closure* scenario (*Mdn = 127.00*) with all other scenario ($p < 0.005$) except for *Three-Closures* scenario (*Mdn = 131.00*) with $p = 0.089$. All other scenario combinations were approximately significantly similar. For *HGV*, the post hoc analysis revealed statistically significant differences in AVTT scores of *Zero-Closure* scenario (*Mdn = 136.00*) and *One-Closure* scenario (*Mdn = 140.00*) with all other scenarios, $p < 0.05$, but not between any other scenario combination. The post hoc test for Bus showed that pairwise comparison between all combinations of scenarios, was approximately statistically similar. Table 6 shows the median values for Car, HGV and Bus categories.

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.

Table 6
Median values per vehicle categories.

Closure	Car		HGV		Bus	
Scenarios	N	Median	N	Median	N	Median
Six	74	137.00	73	152.00	65	132.00
Five	74	134.00	73	148.00	73	133.00
Four	74	135.50	73	147.00	70	135.50
Three	74	131.00	74	145.00	73	128.00
Two	74	133.00	73	148.00	66	129.50
One	74	127.00	73	140.00	69	128.00
Zero	74	126.00	73	136.00	71	128.00

Table 7
Mean ranks per vehicle categories.

Closure Scenarios	Undeclared N	Undeclared Mean Rank	Missed-Detect N	Missed-Detect Mean Rank
Six	14	33.68	14	24.21
Five	8	31.88	15	39.30
Four	13	29.27	10	24.85
Three	11	37.55	6	21.50
Two	10	30.40	8	32.62
One	7	27.43	3	9.67
Zero	0	N/A	0	N/A

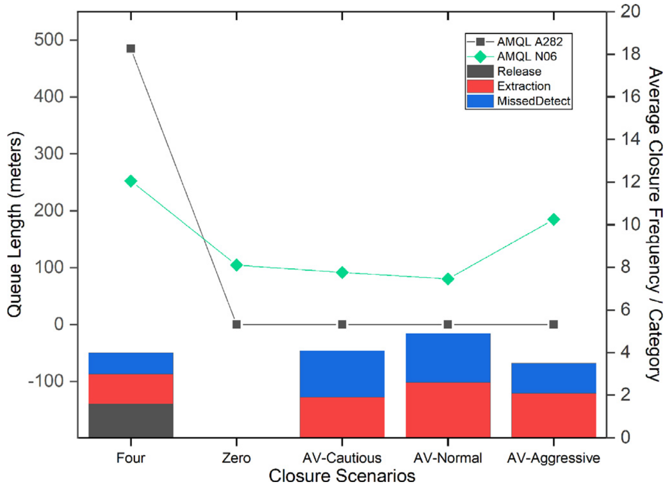

Fig. 4. Phase II Results – AMQL plots for varying scenarios.

Table 7 shows the mean ranks for *Undeclared* and *Missed-Detect* categories.

A one-way ANOVA 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*.

3.2. Phase II – CAV-F vehicles

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

3.2.1. Queue length analysis

Fig 4 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.

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 box-plots. 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 as in Table 8.

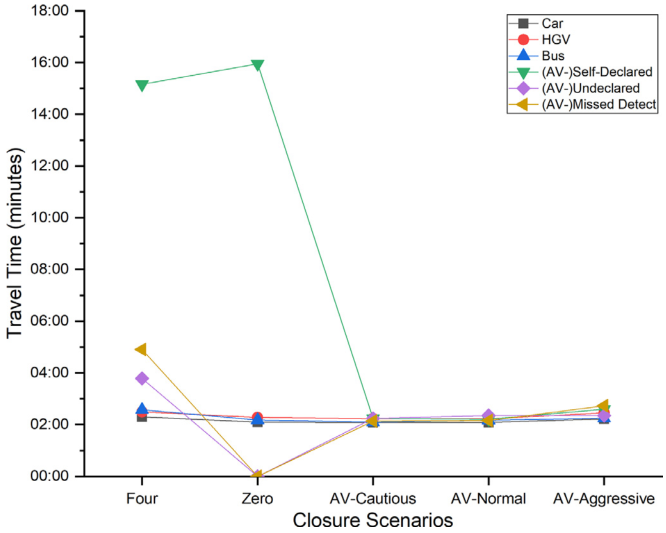

Fig. 5. Phase II Results – AVTT per vehicle categories for varying scenarios.

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 [30–32], 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 revealed that the mean increase from *4-Closure* scenario to *AV-Aggressive* (*1.25, 95% CI [1.01, 1.54]*) was statistically significant (*p = 0.036*), as well as the increase from *Zero-Closure* (2.24*, 95% CI [1.80, 2.80], p < 0.001*), *AV-Cautious* (2.68*, 95% CI [2.10, 3.41], p < 0.001*) and *AV-Normal* (3.00*, 95% CI [2.38, 3.78], p < 0.001*). The mean increase from *AV-Aggressive* to *Zero-Closure* (*1.80, 95% CI [1.56, 2.07]*) was statistically significant (*p < 0.001*), as well as the increase from *AV-Cautious* (*2.15, 95% CI [1.80, 2.55], p < 0.001*) and *AV-Normal* (2.40*, 95% CI [2.06, 2.81], p < 0.001*). The mean increase from *Zero-Closure* to *AV-Cautious* (*1.19, 95% CI [0.99, 1.43]*) was not statistically significant (*p = 0.072*) but from *AV- Normal* (*1.34, 95% CI [1.13, 1.58]*) was statistically significant (*p < 0.001*). Finally, the mean increase from *AV-Cautious* to *AV-Normal* (1.12*, 95% CI [0.92, 1.37]*) was not statistically significant (*p = 0.501*).

3.2.2. Vehicle travel time analysis

Fig 5 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.

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, $p < 0.05$. Table 9 details tests results for individual categories.

Table 8

Normality comparison for AMQL on transformed data $log_{10}(N06)$.

Closure Scenarios	Shapiro-Wilk (α)	Skew	Skew Std. Error	Kurtosis	Kurtosis Std. Error
Four	<0.001	−0.963	0.309	0.414	0.608
Zero	0.169	−0.302	0.309	−0.175	0.608
AV-Cautious	0.039	0.322	0.309	−0.812	0.608
AV-Normal	0.051	0.415	0.309	1.563	0.608
AV-Aggressive	0.144	−0.544	0.309	−0.140	0.608

Table 9

Normality comparison of AVTT in Phase II.

Closure Scenarios	N	Shapiro-Wilk (α)	Skew	Skew Std. Err	Kurtosis	Kurtosis Std. Err
Car						
Four	74	0.037	0.532	0.279	0.267	0.552
Zero	74	<0.001	−5.149	0.279	37.837	0.552
AV-Cautious	74	<0.001	−6.817	0.279	54.211	0.552
AV-Normal	74	<0.001	−5.011	0.279	35.654	0.552
AV-Aggressive	74	<0.001	−4.591	0.279	31.630	0.552
HGV						
Four	73	0.196	0.463	0.281	−0.241	0.555
Zero	73	0.481	0.099	0.281	0.549	0.555
AV-Cautious	73	0.007	0.678	0.281	0.502	0.555
AV-Normal	73	0.001	0.742	0.281	0.553	0.555
AV-Aggressive	74	<0.001	−2.562	0.279	14.646	0.552
Bus						
Four	70	<0.001	5.805	0.287	40.730	0.566
Zero	71	<0.001	1.977	0.285	5.060	0.563
AV-Cautious	71	0.157	0.454	0.285	−0.042	0.563
AV-Normal	72	<0.001	3.302	0.283	12.011	0.559
AV-Aggressive	73	<0.001	1.062	0.281	1.949	0.555
(AV) Self-Declared						
Four	69	0.157	0.185	0.289	−0.611	0.570
Zero	69	0.269	−0.137	0.289	−0.763	0.570
AV-Cautious	73	<0.001	3.258	0.281	14.607	0.555
AV-Normal	73	0.611	0.074	0.281	−0.475	0.555
AV-Aggressive	73	<0.001	1.760	0.281	2.516	0.555
(AV) Undeclared						
Four	13	0.025	−0.404	0.616	−1.695	1.191
Zero	0	N/A	N/A	N/A	N/A	N/A
AV-Cautious	17	0.001	2.083	0.550	4.759	1.063
AV-Normal	20	0.001	1.857	0.512	3.422	0.992
AV-Aggressive	19	0.006	0.948	0.524	−0.449	1.014
(AV) Missed-Detect						
Four	10	<0.001	3.053	0.687	9.502	1.334
Zero	0	N/A	N/A	N/A	N/A	N/A
AV-Cautious	21	0.043	1.160	0.501	1.097	0.972
AV-Normal	19	0.770	0.517	0.524	0.686	1.014
AV-Aggressive	15	<0.001	2.428	0.580	4.931	1.121

Using the Levene's test, assumption of homogeneity was violated for all vehicle categories, $p < 0.001$. By analysing the histogram, box plots and significant outliers for all the vehicle categories, 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. Distributions of *Car, HGV, Bus* and *(AV) Missed-Detect* categories were approximately similar for all the scenarios, as assessed by visual inspection of a boxplot. Median AVTT scores were approximately statistically similar between the closure scenarios for all four vehicle categories, *Car* ($\chi^2(4) = 213.163,\ p < 0.001,\ N = 370$); *HGV* ($\chi^2(4) = 206.139,\ p < 0.001,\ N = 366$), *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 revealed that AVTT scores were approximately statistically similar between the pairs of *AV-Normal* and *AV- Cautious* ($p = 1.000$), *AV-Cautious* and *Zero-Closure* ($p = 0.278$) and *Four-Closures* and *AV-Aggressive* ($p = 1.000$). All other scenario combinations were statistically significantly different ($p < 0.012$). For *HGV*, the post hoc analysis revealed that AVTT scores were approximately statistically similar between the pairs of *AV-Normal* and *AV-Cautious* ($p = 1.000$) and *Four-Closures* and *AV-Aggressive* ($p = 1.000$). All other scenario combinations were statistically significantly different ($p < 0.004$). The post hoc test for *Bus* showed that AVTT scores were approximately statistically similar between the pairs of *AV-Normal* and *AV-Cautious* ($p = 1.000$), *AV-Normal* and *Zero-Closure* ($p = 0.463$), *AV-Cautious* and *Zero-Closure* ($p = 0.581$) and *Four-Closures* and *AV-Aggressive* ($p = 1.000$). All other scenario combinations were statistically significantly different ($p < 0.04$). Finally, the post hoc test for *(AV) Missed-Detect* vehicle category revealed that the AVTT scores were approximately statistically similar between all the scenario combinations, except for *AV-Cautious* and *Four-Closures* ($p < 0.001$) and *AV-Normal* and *Four-Closures* ($p < 0.001$) where scores were statistically significantly different. Table 10 shows the median values for *Car, HGV, Bus* and *(AV) Missed-Detect* categories.

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, $\chi^2(3) = 32.501,\ p < 0.001, N = 69$. The pairwise comparisons were performed using Dunn's procedure with a Bonferroni correction for

Table 10
AVTT median values in seconds.

Closure Scenarios	Car N	Car Mdn	HGV N	HGV Mdn	Bus N	Bus Mdn	(AV) Missed-Detect N	(AV) Missed-Detect Mdn
Four	74	135	73	147	70	135	10	280
Zero	74	126	73	136	71	128	0	0
AV-Cautious	74	125	73	133	71	127	21	127
AV-Normal	74	125	73	133	72	127	19	129
AV-Aggressive	74	135	74	147	73	133	15	134

Table 11
AVTT mean ranks for vehicle categories.

Scenarios	*(AV) Self-Declared* N	*(AV) Self-Declared* Mean Rank	*(AV) Undeclared* N	*(AV) Undeclared* Mean Rank
Four	69	285.56	13	61.58
Zero	69	291.44	0	N/A
AV-Cautious	73	86.05	17	20.71
AV-Normal	73	85.58	20	30.50
AV-Aggressive	73	158.36	19	34.34

independent closure scenarios of both the vehicle category. The post hoc analysis for *(AV) Self-Declared* vehicle category revealed AVTT to be approximately statistically similar for the pair *AV-Normal* and *AV-Cautious* scenarios ($p = 1.000$) and *Four-Closures* and *Zero-Closure* scenarios ($p = 1.000$), but statistically significantly different for all other scenario combinations. For *(AV) Undeclared* vehicle category, the post hoc test showed statistically significant different AVTT scores for *Four-Closures* scenario with *AV-Cautious* scenario ($p < 0.001$), *AV-Normal* scenario ($p < 0.001$) and *AV-Aggressive* scenario ($p = 0.002$). Table 11 shows the mean ranks for *(AV) Self-Declared* and *(AV) Undeclared* vehicles.

4. Discussion

From the results, it can deduce 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 note the mixed impact of AV vehicles on queue formations and travel time, especially for *AV-Aggressive* driving behaviour which was observed to be significantly different in comparison to *AV-Cautious* and *AV-Normal* scenarios.

Analysing the results for the conventional vehicles queue measurement, 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 min 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 DGV and ALV 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. This statement is further supported by the results in *Phase II*, which shows significant improvements in reduction of queues and travel times, limited only to *AV-Cautious* and *AV-Normal* driving behaviour. In contrast to the two autonomous driving scenarios, the *AV-Aggressing* driving method performed significantly worse than the two AV categories, both for queues and travel time 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. In contrast, the queue length for *AV-Aggressive* scenario 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 m were more frequent, even with zero queues on A282. The reason for this could be disproportionately low traffic count of CAV-F vehicles against conventional vehicles for *AV-Aggressive* and sensitive driving parameters to ensure near perfect simulation of fully autonomous vehicles.

Analysing the vehicle travel time results for *Phase I*, it was revealed that, AVTT for *Car, HGV* and *Bus* vehicle categories was considerably low at ∼ 2.5 *min* with an observed maximum delay of approximately a minute, during a free-flow period. For *Car* and *HGV, 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 min and AMTT of ∼ 6 min, 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 min.

The biggest impact on the travel time was observed for the *Self-Declared* vehicle category with AVTT of ∼ 15 min and AMTT of ∼ 40 min. 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 *DGV* and *ALV* vehicles must always stop at KMA for inspection. The average delay for this category was observed at ∼ 10 min for vehicles which were resent to A282 via N06 and ∼ 3 min 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 min to ∼ 10 h, 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 matches real-world, where up to nine vehicles are queues for an unknown duration before they are released.

Comparing the results from *Phase I* and *Phase II* for travel time measurements, it could be observed that *AV-Cautious* and *AV-Normal* scenarios performed significantly better than conventional vehicle scenarios. 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, HGV* 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 min 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, HGV* and *Bus* improved by ∼ 104%, ∼ 59% and ∼ 37%, respectively, i.e. an improvement of ∼ 4 min for *Car* and *HGV* categories and ∼ 2 min for *Bus*. The biggest winner was the *Self-Declared* category for which AMTT improved by ∼ 18 min, 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 s, respectively.

5. Conclusion

The aim of the paper was to determine the impact of Connected and Autonomous Freight Vehicles (CAV-F) implementations near a road tunnel to help mitigate congestion and travel time. The positive results from the traffic simulations highlighted the advantages of Connected and Autonomous Vehicles. It was interesting to see that by only replacing conventional Dangerous Good Vehicles and Abnormal Load Vehicles categories to CAV-F, significant improvements were achieved in reducing the travel time and road traffic queues. Though, it was observed that an 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 emphasis on importance of connectivity in Connected and Autonomous Vehicles technology and shows that if a valid Vehicle-2-Infrastructure communications are 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 haulier companies by increasing their productivity and turnaround time. So to summarise:

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

As the scope of the study was to understand the potential benefits of limited CAV-F implementations, future research work could analyse how the connectivity element of Connected and Autonomous Vehicles be implemented to optimise the throughput via a tunnel. Also, future studies could expand the model to consider complex traffic conditions involving planned or unplanned incidents to study the behaviour of CAV-F vehicles under such conditions.

Declaration of Competing Interest

None.

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