Traffic Simulation of Connected and Autonomous Freight Vehicles to Increase Traffic Throughput via Road Tunnel Networks

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***Abstract*— This paper simulates traffic at the Dartford-Thurrock Crossing Tunnel, Kent, UK. Using a traffic simulation model, Connected and Autonomous Freight Vehicles (CAV-F) are simulated alongside conventional light goods vehicles, to determine the feasibility of increasing the traffic throughput at the tunnel. The results show that with the use of CAV-F, the overall traffic flow is increased by ~33% from current flow of ~5,000 vehicles/hr. With the reduction in the headway and standstill distance and increase in scope of intelligent connectivity and traffic speed limit, the average congestion and travel time are reduced even at a higher traffic concentration. By analysing the results, it has thus been possible to highlight the benefits to traffic management and road utilisation by introducing CAV-F into our road network, in the long term.**

Keywords—Connected and Autonomous Vehicles, Traffic Modelling, Road Tunnels, Road Traffic, Freight, Autonomous Driving

I. INTRODUCTION

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 tunnel [1]. To ensure the safe travel through a tunnel and not to have a repeat of Mont Blanc [2] and Tauern tunnel incidents, numerous tunnel monitoring procedures and technologies are set in place. Additional restrictions observing the European Agreements concerning the International Carriage of Dangerous Goods by Road (ADR) regulations are applied to govern the flow of dangerous goods vehicles (DGV) via a road tunnel on a Trans-European Transport Network (TEN-T). In the UK, check-and-allow procedures for DGV and abnormal load vehicles (ALV) are implemented either using tolls prior to the tunnel, or by using sensors to detect the physical dimensions of a vehicle, or orange plate labels for hazardous goods carriages. The latter implementation using sensors is only used at Dartford-Thurrock Crossing tunnel in Kent, UK.

Although the importance of these precautionary measures are inevitable, the undesirable consequences of increased congestion, travel delays, higher fuel consumption and micro-pollution cannot be ignored. With current traffic environments involving conventional vehicles and no connected infrastructure to communicate verification exchanges for vehicle dimensions and goods carriage, the problem pertaining to tunnel checks cannot be resolved. But with the technological advancements in Cooperative and Intelligent Transportation Systems (C-ITS) and communications between Vehicle-2-Vehicle (V2V) and Vehicle-2-Infrastrucutre (V2I), the traffic-related problems could be solved using Connected and Autonomous Freight Vehicles (CAV-F). The usefulness of C-ITS solutions is discussed in previous study [3] on improving tunnel safety. The report on Stockholm Bypass Tunnel [4] mentions the use of C-ITS solutions to improve traffic and emergency management. Another study [5], 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.

In this paper the study aims to determine the role of CAV-F in improving congestion (measuring Average Maximum Queue Length (AMQL)) and travel time with increasing volume of traffic near a road tunnel.

II. AIMS AND OBJECTIVES

In UK there are nine tunnels on TEN-T network which must adhere to strict ADR regulations to control the movement of DGV [6]. Out of the nine tunnels, six tunnels are classified as category E, where by no DGV are allowed. The Mersey and Clyde road tunnels are of category D and are equipped with toll booths to govern the flow of traffic. The Dartford Crossing tunnel classified as category C tunnel which does not allow vehicles with carriage exceeding total net explosive mass of 5000kgs per transport unit. Additionally, there are other specific operating restrictions [7] relating to the passage of DGVs. To control the flow of DGV the tunnel is equipped with sensors and traffic signals to ensure only complaint vehicles travel via the tunnel. As the tunnel does not have toll booths, the traffic is mostly free-flowing except for the scenarios where the traffic is stopped to escort or extract DGV as per tunnels functional requirements.

As the Dartford Crossing tunnel is already an improvement on the tunnels with toll booths, in this paper, the study aims to determine the feasibility of CAV-F in increasing the throughput of traffic at Dartford Crossing tunnel. The case study conducted on Dartford Crossing tunnel in 2009 [8] highlighted that, the four-lane A282 road section should be able to support at least 7,000 vehicles per hour but currently saturates at ~4,000 vehicles/hr (or ~5,000 vehicles/hr following the removal of toll booths in 2016, based on Dartford Crossing data analysis). The research hypothesises that by replacing the conventional freight vehicles with CAV-F, the A282 four-lane road section would be able to accommodate 7,000 or more vehicles per hour without impacting the traffic flow and journey time.

By increasing the traffic speed limit, reducing the headway

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TABLE I. CAV-F DRIVING BEHAVIOURS USED IN 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

and standstill distance, and improving the connectivity with other vehicles and road infrastructure, the aim of increasing traffic flow would be achievable. The assumption is made on the basis 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. It is also assumed that the tunnel being CAV-enabled the scenarios of escorting and extracting DGV would be eliminated.

III. METHOD

The study is based on the data (observed between 1st March 2017 and 15th February 2018) obtained from the Dartford Crossing tunnel with appropriate permissions obtained from Highways England. From the data, the annual average daily traffic (AADT) was observed at ~3,300 vehicles per hour, with a typical peak hour AADT at ~4,700 vehicles. The traffic composition was identified as ~80.73% light goods vehicles (LGV), ~17.64% heavy goods vehicles (HGV) and ~1.63% others. The traffic composition was grouped as per ECTN classification of SICK sensors [9]. The traffic simulation software, PTV Vissim version 11 [10], was used in the research to model the Dartford Crossing traffic flow and comparing the simulations measuring the performance of CAV-F driving alongside conventional LGV traffic, as the traffic flow is increased from 5,000 vehicles/hr to 10,000 vehicles/hr. The model mimics the A282 four-lane road leading towards a two bored tunnel, West bore and East bore, Junction 1A (J1A), and nearby A206 roads with a roundabout. The model implements the eight traffic signals at A206 roundabout using the Fixed Time add-on module of PTV Vissim to mimic their real-world counterparts.

As the study assumes intelligent communications between vehicles and infrastructure to replace check-and-allow procedures, the sensors and traffic signals installed before Dartford Crossing tunnel are omitted from the simulation model as their sole purpose was to capture non-compliant DGV and ALV vehicles and stop their entry in the tunnel. The traffic flow information and vehicle routing percentages for different road sections apart from J1A and A206 roads is obtained from Dartford Crossing data. Traffic flow on J1A and A206 road sections are approximated using traffic flow count obtained from DfT [11].

In the simulation model, CAV-F driving behaviours is defined using existing autonomous driving behaviours in PTV Vissim based on the CoEXist project [12] with the Wiedemann 99 [13] car following model. The LGV category is simulated using *Car* vehicle category as the driving behaviour with desired minimum and maximum acceleration at 0.39m/s^2 and 1.38m/s^2 respectively and desired minimum and maximum deceleration at -3.00m/s^2 and -2.55m/s^2 respectively at 80 km/h speed limit. The lower-upper bound weight and power distributions used for the *Car* category are 800kgs – 3,500kgs and 55kW – 160kW, respectively.

The simulation scenarios are defined based on four determinants which are noted to be crucial in increasing the traffic flow. These determinants 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 [14] and are only limited to *CAV-F* vehicle category when the preceding vehicle is also a CAV-F. TABLE I. defines four different driving behaviours used in the simulations. 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 project behaviours, pre-defined in PTV Vissim and *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 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 free-flow 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). As the study [15] highlights the improved driving performances of CAV vehicles at higher speeds, the increased speed limits are only applied to four AV driving behaviours.

To test the hypothesis, the hourly simulation results are analysed based on the average of ten simulation runs, randomised using PTV Vissim's random seed generator [16] which creates unique vehicle simulation initial conditions.

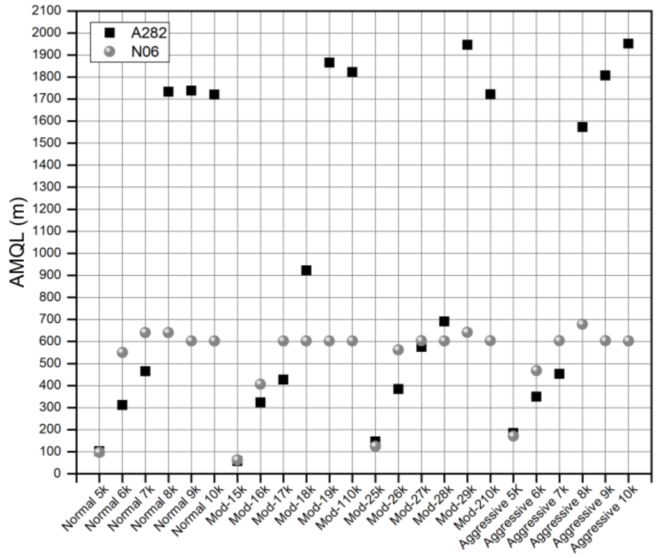

Fig 1 AMQL plot for varying vehicle counts and driving behaviours

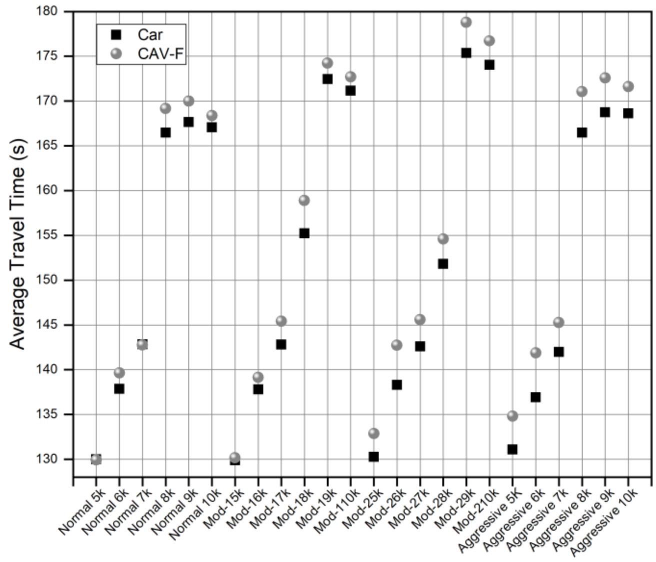

Fig 2 Average travel time for varying vehicle counts and driving behaviours

This ensures no two simulations are similar as observed in the real-world. The results are then compared and discussed for AMQL and average travel time measurements to support the hypothesis. The study does not consider road conditions pertaining to accidents, unplanned or planned incidents or planned tunnel closures.

IV. RESULT

The overall analysis of results show that with the use of *AV-HGV* vehicles, the tunnel road network could cope with 7,000 vehicles/hr traffic flow. The results are discussed for AMQL and average travel time measurements in two groups. The first group, *Driving Behaviour Changes*, will analyse performance between four driving behaviours mentioned in TABLE I. for varying traffic flow, 5,000 vehicles/hr to 10,000 vehicles/hr. The second group, *Traffic Speed Limit*, will analyse the performance of varying speed limits: 80 km/h, 88 km/h, and 96 km/h for four identified driving behaviours with fixed 7,000 vehicles/hr traffic flow.

A. *Driving Behaviour Changes*

1) *AMQL Analysis*

Fig 1 shows the AMQL results. The analysis showed that overall *Mod2* version of AV driving behaviour performed better than the other driving behaviours. On the A282 road section, *Mod2* was able to restrict the AMQL to ~700 m with traffic flow up to 8,000 vehicles/hr and *Mod1* to ~900 m. The vehicle count of 8,000 vehicles/hr 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 ~100 m to ~350 m) as the vehicle count was increased from 5,000 vehicles/hr to 6,000 vehicles/hr. The AMQL increment for 6,000 vehicles/hr to 8,000 vehicles/hr was comparatively steady for *Mod2* and *Mod1* driving behaviours at ~17% and ~49% respectively but was significantly higher for *Normal* and *Aggressive* driving behaviours, at ~66% and ~85%. Also, both *Normal* and *Aggressive* driving behaviours were unable to cope with traffic flow greater than 8,000 vehicles/hr and AMQL was ~1750 m on average.

In contrast, the analysis of AMQL on N06 showed that 6,000 vehicles/hr is the tipping point and average queue length is ~500 m. With traffic flow greater than 7,000 vehicles saturates the flow on N06 as the AMQL is ~600 m, the full length of N06. The reason for this could be the higher proportion of conventional LGV on A206 road 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 [8], aligns with the finding which stated that a four-lane road network should be able to support 7,000 or more vehicles per hour.

2) *Travel Time Analysis*

Fig 2 shows the plot of average travel time over 10 simulation runs of individual vehicle counts and driving behaviours. The analysis showed that average travel time pattern is similar to AMQL plot. Further analysis showed that *Mod1* and *Mod2* driving behaviours were statistically similar and *Normal* and *Aggressive* were statistically similar. It was observed that 8,000 vehicles/hr was the tipping point and travel time was increased by ~8% (11 seconds) for *Mod1* and *Mod2* driving behaviours and by ~18% (25 seconds) for *Normal* and *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/hr to 6,000 vehicles/hr. The results also showed that the average travel time for *CAV-F* vehicle category was always slower than conventional *Car* category. On average, for *Normal* the difference was ~1.5 seconds, for *Mod1* ~2 seconds, for *Mod2* ~3 seconds and for *Aggressive* driving behaviour ~4 seconds.

It is interesting to observe that even with AMQL ranging between ~100 m to ~2, 000 m, 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.

Fig 3 shows the average delay observed during simulations

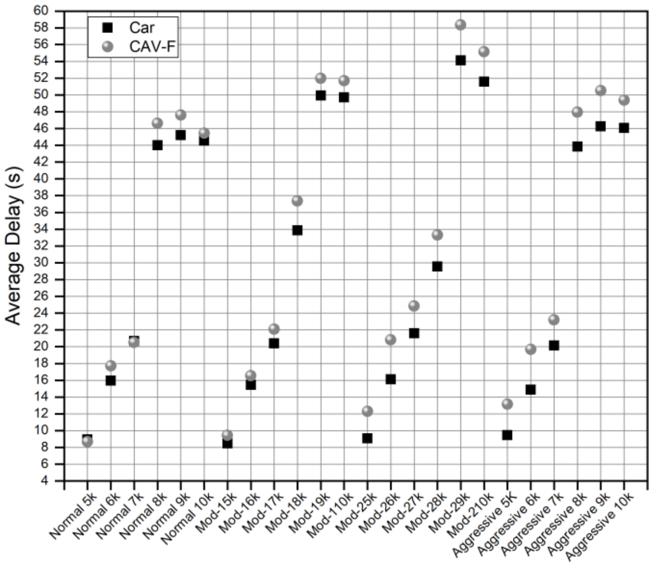

Fig 3 Average delay plot of varying vehicle counts and driving behaviours

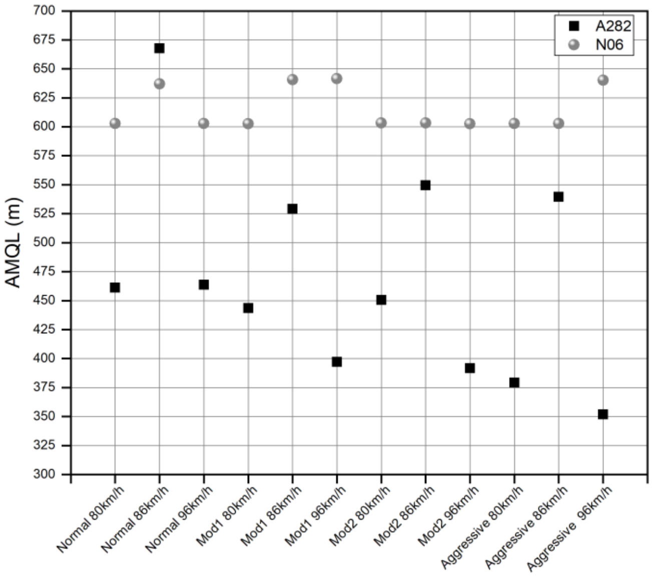

Fig 4 AMQL plot for fixed vehicle count and varying speed limits for different driving behaviours

and the analysis points that delay ranges from ~9 seconds to ~58 seconds as traffic count is incremented from 5,000 vehicles to 10,000 vehicles on an hourly basis.

B. *Traffic Speed Analysis*

From the analysis in section A, it was identified that by using CAV-F the traffic flow of 7,000 vehicles/hr is achievable. In this section, the results for changes in speed profiles will be analysed to support the argument that by increasing the speed limit on A282 road section improved traffic performance could be obtained for 7,000 vehicles/hr traffic flow scenario. The results will be studies for AMQL and average travel time measurements.

1) *AMQL Analysis*

Fig 4 shows the AMQL plot for varying speed limits. The analysis showed that, interestingly the 86 km/h (55 mph) speed limit scenario performed worse than 80 km/h (50 mph) and 96 km/h (60 mph) speed limits for all driving behaviours, for both A282 and N06 road sections. On A282, for *Mod1* and *Mod2* the 86 km/h speed limit scenario was ~24% worse and for *Normal* and *Aggressive* the speed limit was ~38% worse

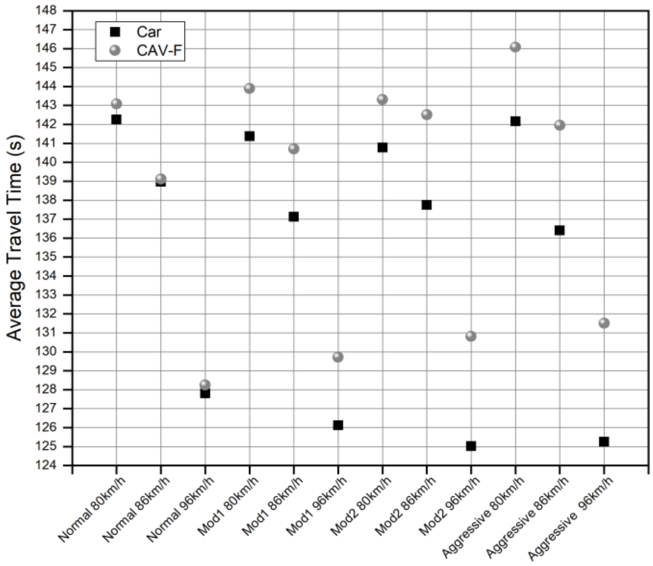

Fig 5 Average travel time plot for fixed vehicle count and varying speed limits for different driving behaviours

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 *Normal* 80 km/h, Mod1 86 km/h, Mod1 96 km/h, and *Aggressive* 96 km/h 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 *Normal* the AMQL improved at 96 km/h (60 mph) speed limit by ~7.5% from 80 km/h (50 mph). The *Mod2* driving behaviour performed best with an improvement of ~13% in improving AMQL.

2) *Travel Time Analysis*

Fig 5 shows the analysis of average travel time for varying speed limits. The results showed that all the driving behaviours were able to reduce average travel time as the speed limit was increased from 80 km/h (50 mph) to 96 km/h (60 mph). Comparing the *Car* and *CAV-F* vehicle categories, the biggest improvement was observed for *Car* vehicle category, especially for *Mod1* with ~2.5%, *Mod2* with ~3% and *Aggressive* with ~4% improvement in average travel time. For *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 *Normal* to *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/h (60 mph) speed limit scenario.

Fig 6 shows the analysis of average delay which emphasis on the findings that *CAV-F* vehicle category was not benefited with changes in driving behaviour and average delay for this vehicle category was significantly higher by ~17.5% as compared to *Car* vehicle category.

V. Conclusion And Future Works

This paper analysed the impact of simulated CAV-F in improving the traffic throughput at Dartford Crossing tunnel.

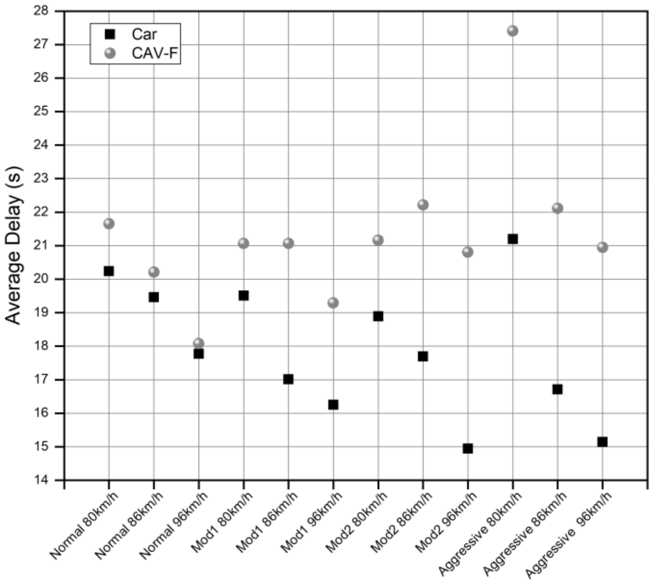

Fig 6 Average delay plot for fixed vehicle count and varying speed limits for different driving behaviours

Assuming the technology to ensure safe and secure V2V and V2I was in place, this study focused on different driving. 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 *Mod2* driving behaviour the Dartford Crossing 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. This advocates the case for connected and autonomous vehicles 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.

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.

VI. Discussion

As the benefits of using connected freight vehicles are realised in the paper using the traffic simulation on existing infrastructure with increasing traffic, the challenge remains to assess the findings in real-world. To enable the full potential of CAV-F, it would be imperative that the road tunnel infrastructure is equipped with secure V2I technologies alongside conventional signs and signals to ensure non-connected vehicles are equally informed about road surroundings. Legislative and operative changes would be required ensure safe movement of connected vehicles alongside conventional vehicles. Overcoming such challenges would ensure increase in traffic could be sustained on existing roads without costly expansions. Coordinated and connected with wider road networks, the supply chain of freight industry would be improved benefiting socio-economic progress.

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