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Redesigning roadway infrastructure for mixed autonomous and non-autonomous traffic

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Abstract

Autonomous vehicles are likely to be one of the major forms of disruptive technology that will be affecting travel behaviour and transport infrastructure development. During the last century, roads have been designed to provide a safe, approachable and efficient environment for the navigation of human drivers in conventional vehicles. The presence of enhanced driving behaviours, such as precise lane guidance and near instantaneous reaction times within autonomous vehicles will transform the planning and design of roadway infrastructure. Acknowledging and leveraging these aspects in coordination with the optimisation of the interaction between conventional and autonomous vehicles will be pivotal for the sustainable adoption of the technology.

This study focusses on facilitating mixed autonomous and non-autonomous roadway sharing through two potential redesign options. These are modelled in a microsimulation traffic modelling environment to assess the operational impact of a variety of autonomous vehicle penetration rates, across three demand scenarios. The first option reassigns a single lane as an "autonomous vehicle only" lane on a network consisting of major arterials and motorways. The second redesign consists of reserving entire links of a parallel grid network layout for autonomous vehicles, thus separating general traffic and autonomous vehicle only links.

The results from the microsimulation modelling indicate that both proposals present improvements in network performance, evident through increased speeds and reduced delay times. However, improvements are observed only in select scenarios. The analysis highlights that the success of the proposed redesigns are primarily dependent on the level of traffic demand and the technology penetration percentage. Accordingly, the development and redesign of roadway infrastructure must be carefully considered in light of adoption rates to obtain an effective incorporation of autonomous vehicles within the transport system.

1. Introduction

Autonomous vehicles offer a broad range of benefits to the transport system, such as the potential for drastically safer and more accessible transportation in comparison to human driven vehicles. However, they also pose risks, such as worsened traffic congestion due to increased levels of private vehicle travel and complex legal and ethical questions surrounding insurance and responsibility in crash scenarios. Nonetheless, the likely shift towards increasing driverelss adoption in the future offers an opportunity to redesign existing infrastructure in order to facilitate the ideal sharing of road space in the mixed autonomous and non-autonomous environment. Thus, this study investigates the need for modifications of the road network to sustainably integrate autonomous vehicles and provides suggestions of potential redesign alternatives to cater for the new vehicle type. The first redesign presented examines reassigning a single lane as an autonomous vehicle only lane on a network based on a major arterial and motorway. The second redesign reserved alternating links in a parrallel grid network layout to separate general traffic and autonomous vehicle only links. The impacts and effectiveness of these two redesigns have been examined using two microsimulation models for a range of demand scenarios and penetration percentages.

2. Literature review

A plethora of autonomous vehicle research has been conducted in the past focusing on vehicle algorithm development, disengagement and reliability as well as market penetration. However, clear definitions on terminology associated with autonomous vehicles remain inconsistent without a standard approach in describing the vehicle or ancillary technology. This study will refer to autonomous vehicles primarily as Connected Autonomous Vehicles (CAVs) which will be understood as bearing V2V and V2I connectivity and possessing Level 4 or Level 5 automation but operating in a fully autonomous fashion.

While redesigning roadways for autonomous vehicles is still a relatively novel concept, a number of studies have examined the impacts of redesign options. CAV only zones are proposed as a way to separate conventional and CAV traffic to maximise benefits across the network. Chen et al (2017) introduced a mathematical framework for the optimal strategic design of a CAV zone in a general network. Upon entering a CAV zone, route choice for all vehicles was carried out by a central controller to achieve a system optimal assignment. The study found that the implementation of the CAV zone could reduce total system travel time by 21.4%, and by over 50% within the CAV zone. (Chen el al, 2017)

CAV only lanes have also been proposed as a means of enabling a safer and more efficient road environment. High penetration percentages of CAVs are able to operate with characteristics enabling better network performance, such as reduced traffic headways enabling increased road capacity (Fagnant & Kockelman, 2015). However, this behavior can be constrained by the presence of non-CAV vehicles within the network. CAV lanes offer a means to separate connected traffic into dedicated lanes – which could have significantly higher capacities than regular lanes and be implemented well before CAVs become the dominant vehicle type on the road (He et al, 2016). Talebpour et al (2017) examined some of the ways in which a CAV lane could be implemented in a two lane and four lane highway segment for a range of different reserved lane usage scenarios including mandatory usage, optimal usage and limited usage. The modelling undertaken by Talebpour et al (2017) found that optimal usage of the reserved lane could deliver potential benefits once CAVs reached market penetrations of 30% and above for four lane highways, and 50% and above for two lane highways. On the other hand, deployment of CAV lanes prior to CAVs reaching an adequate penetration level, or restricting CAVs to only use the reserved lane both resulted in significant detriment to the performance of the network.

In contrast to Talebpour et al (2017), Ivanchev et al (2017) also examined the potential of a CAV lane but concluded that it was not beneficial in terms of average commute time based on a macroscopic model of the city of Singapore under user equilibrium. Nonetheless, despite showing reduced network performance, Invanchev et al (2017) also showed that CAVs recorded significantly improved performance (~25%) at the cost of worsened conventional vehicle travel time (~7%) in certain scenarios. Additionally, Ivanchev et al (2017) concluded that after a certain penetration percentage, the impact of the CAV lane becomes negligible. Given the diverging results of these studies, as well as the large number of options and scenarios in which redesigns could be implemented, it is clear that further research is necessary to have a more robust understanding of the impacts of redesigns options on facilitating mixed autonomous and non-autonomous roadway usage.

Recent studies, as presented in the literature review, have examined the impact of infrastructure modifications to enable improved roadway function. These studies have provided this study with the motivation to examine different infrastructure modifications which can facilitate improved sharing of roadways between autonomous and non-autonomous traffic. This analysis is enabled through microsimulation of two redesign options using customised vehicle parameters to represent CAVs, as well as a custom car following model plugin. In particular, this study focusses on identifying and understanding the relationships between different redesign options, CAV penetration levels, travel demand levels and the impacts of these factors on different network performance measures.

3. Methodology

In order to test the effectiveness of possible redesigns for mixed autonomous and non-autonomous traffic, firstly, two different redesign options were selected based on the available literature as presented in Section 2. These redesign options were applied to two real world inspired traffic models which were then tested using the Aimsun traffic simulation software with custom parameters and a plugin enabling simulation of CAV-like characteristics.

3.1 Selection of proposed redesign options

Chen et al (2017) simulated significant improvements in total system travel time through the creation of CAV-only zones which helped segregate autonomous and non-autonomous traffic. Cognisant of this finding, this study examines the proposal to restrict certain roads within a network for “CAV only” usage in order to gain an understanding of the possible costs and benefits of such a layout. However, instead of restricting a ‘zone’ as a set of two or more parallel links, this study restricts alternating roads within a grid network. This is considered preferable in comparison to a zone in order to minimise the disruptive impact of making a large, concentrated area of a city or suburb inaccessible for human drivers. Thus, restricting alternating links maintains accessibility though designing CAV-only roads such that no two parallel or adjacent roads are restricted to CAV only access.

Additionally, multiple researchers have proposed the creation of a CAV-only lane as a less disruptive alternative to add a degree of separation between human and autonomous traffic. In effect, these would operate similar to a bus or transit lane, allowing only CAVs to utilise them, on an either permanent basis or during certain times of the day. He et al (2016) and Talebpour et al (2017) both found that CAVs were able to reduce travel time through the implementation of CAV only lanes, however, the former showed improved overall network travel time, while the latter recorded worsened overall network travel time. With consideration to these findings, this study will further examine the proposal to implement a restricted CAV only lane on a multi-lane road.

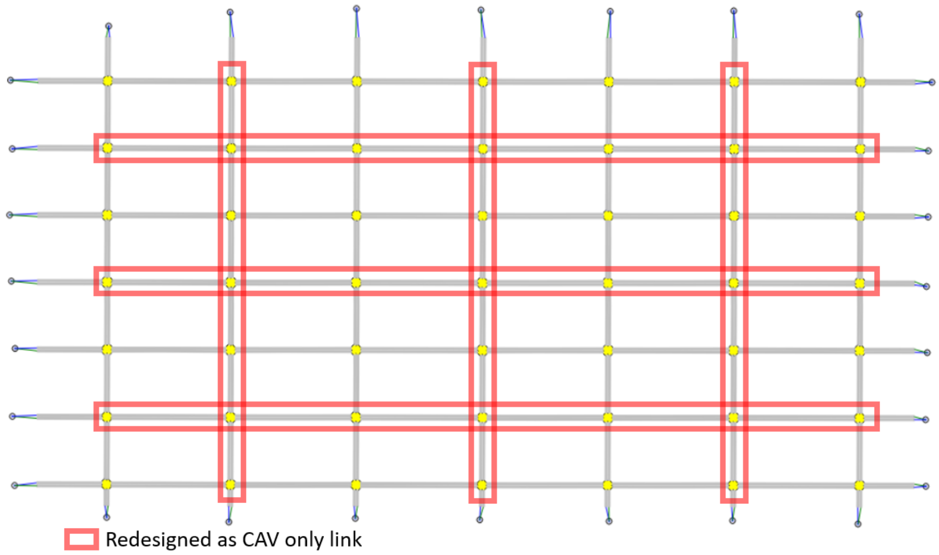
3.2. Microsimulation network models

Two distinct network models were developed to test the network performance, before and after the implementation of the proposed redesign options.

3.2.1 Urban grid network model

The urban grid network model consists of a grid street system with a 7 by 7 layout, 28 origin and destination centroids and 49 signalised intersections. This layout is inspired by the inner-city grid networks common throughout the world and notably present in the Melbourne and Adelaide CBDs in Australia. The network was redesigned in order to implement CAV-only roads on every alternative parallel link, thus restricting 6 out of 14 roadways for CAV-only usage while 8 out of 14 roadways remained allocated for mixed traffic usage. The network is shown in Figure 1.

Figure 1: Urban grid network model

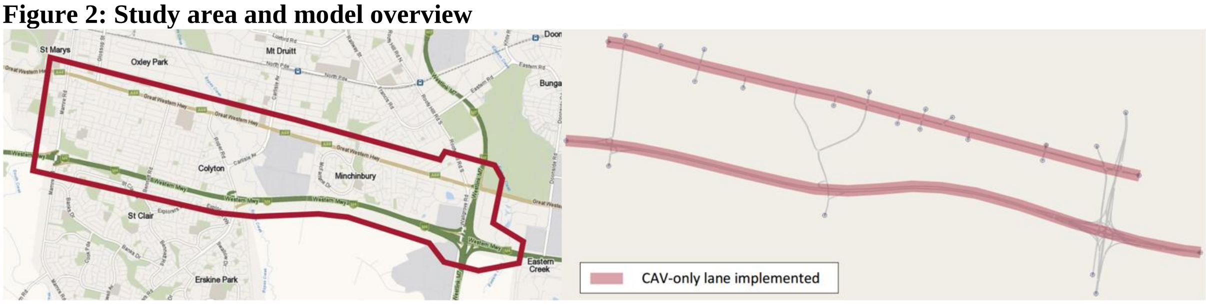


3.2.2 Arterial/ freeway network model

The arterial/freeway network model is based on a real-world corridor in Western Sydney, where the A44 Great Western Highway runs parallel to the M4 Western Motorway.

The network was redesigned in order to implement CAV-only lanes on the entire lengths of the A44 and M4. This included a total of 24 origin and destination centroids and 21 signalised intersections. These two parallel roads consist of three lanes in both directions, where the innermost lane has been restricted as a CAV-only lane while the remaining two lanes were maintained for mixed traffic usage. The CAV lanes were restricted as “Reserved Optional” within Aimsun, resulting in non-mandatory utilisation of the lane by CAVs but the restriction of non-CAVs from entering the lane, other than when using the lane to access a turn lane. An overview of the study area and model is shown in Figure 2.

Figure 2: Study area and model overview



3.3 Microsimulation modelling scenarios

3.3.1 Travel demand scenarios

Accurate prediction of travel demand following the introduction of CAVs is difficult due to the fact that this growth will be shaped by a large number of external factors. Travel demand may decrease due to increased preference of active and public transport options or the more prevalent usage of ridepooling resulting in more journeys being accommodated by fewer vehicles (Rand, 2016). On the other hand, various factors may contribute to an increase in travel demand. These factors include non-drivers who may have not been able to travel in a car by themselves now being able to do so, or the decreased value of time in CAVs resulting in travelers accepting longer travel distances (Litman, 2017). As modelling variations of travel demand is not the focus of this study, three travel demand scenarios will be considered to understand the impact of redesign options:

- *Low Travel Demand*: Representative of quieter time periods such as night-time traffic or low growth in future travel demand.
- *Medium Travel Demand*: Representative of moderately busy periods such as the inter-peak period or of moderate growth in future travel demand.
- *High Travel Demand*: Representative of busy periods such as the peak period or of high growth in future travel demand.

3.3.2 Origin/ Destination travel demand matrices

An intuitive approach was applied to develop the Origin-Destination matrices based on spot observed counts. As this study presents a comparative assessment of a variety of infrastructure scenarios, it is imperative to present a realistic hypothetical demand pattern.

For the Urban Grid Model, it was assumed that vehicles travelling through the network will be aligned a maximum of two roads to the right or left from their final destination road. In contrast, for vehicles turning left or right to reach their final destination road, an even distribution was assumed. This procedure was repeated for all 28 O/D pairs to obtain the O/D matrix. Following this, the three different travel demand scenarios were created via linearly increasing the traffic across the network and observing the performance of the network to replicate conditions representing the low, medium and high congestion scenarios.

For the Arterial/ Freeway Model, an estimated initial O/D matrix was created based on on-site observations, RMS Traffic Volume Viewer and Google Traffic Viewer. The model was then run and iteratively adjusted until a realistic travel state was acquired for the three different demand scenarios.

Table 1: Traffic volumes

Travel Demand Scenario	**Travel Demand (veh/hr)**	
	Urban Grid Model	**Arterial/ Freeway Model**
Low	10,440	14,410
Medium	18,330	30,318
High	20,880	38,388

3.3.3 CAV penetration rate scenarios

Researchers have debated the exact rates of CAV adoption. Littman (2017) predicted 90% of the new car market share to be CAVs by no sooner than 2050, while KPMG (2015) predicted that this market share would be achieved within the next 10 years which are significantly different penetration forecasts.

Thus, this study does not attempt to predict the adoption of CAVs, but rather nine CAV penetration scenarios have been considered; 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90%. As the focus of this study is on mixed traffic, scenarios where CAVs represent less than 10% or more than 90% of the total road traffic were not considered.

3.4 CAV behaviour microsimulation

CAV technology is currently in a period of rapid development and prototyping, making it difficult to make predictions regarding the exact driver behavior which can be expected from CAVs. However, this study assumes two expected modes of CAV driving behaviour. Initially, CAVs will mimic ideal human driver behavior. CAVs will be able to operate perfectly within the current traffic environment, but with a higher level of safety and accuracy as a result of the removal of human error. Thus, CAVs will initially operate similar to the ideal defensive human driver (Calvert et al, 2017).

Following this level of autonomy, it is expected that advanced technological development will enable the second mode of CAV driving behavior. In this mode, CAVs will utilise technologies such as V2V and V2I communication and advanced sensor systems to enable advanced driving behavior such as:

- Stabilised headway and car following (platooning)
- Fast or instantaneous reaction times at traffic signals
- Optimised gap acceptance and gap lane changing between CAVs (Patel et al, 2016).

Despite these advanced driving characteristics, these behaviours will only be enabled in environments where CAVs are not directly travelling with human driven vehicles. Thus, this study assumes that CAVs will operate predominantly with their Mode 1 driving characteristics in mixed traffic environments but with Mode 2 driving characteristics in separated traffic environments, such as in the dedicated CAV only reserved lanes and reserved links.

The base vehicle parameters utilised by Aimsun were modified in order to depict Mode 1 and Mode 2 CAV driving behavior as outlined in Table 2. It is noted that the Human Car vehicle parameters are the standard values used by the software.

Table 2: Aimsun vehicle parameters

Parameter	Human Car	CAV Car
Speed Acceptance – Mean	1.10	1.00
Speed Acceptance – Min.	0.90	1.00
Speed Acceptance – Max.	1.30	1.00
Min Distance Veh – Mean	1.00 m	1.00 m
Min Distance Veh – Min.	0.50 m	1.00 m
Min Distance Veh – Max.	1.50 m	1.00 m
Max Give Way Time – Mean	10.00 sec	15.00 sec
Max Give Way Time – Min.	5.00 sec	8.00 sec
Max Give Way Time – Max.	15.00 sec	20.00 sec
Reaction Time	0.8	0.2
Reaction Time at Stop	1.2	0.2
Reaction Time for Front Vehicle at Traffic Light	1.6	0.2

Additionally, in order to further depict CAV behvaiour within the models, an Aimsun plug-in developed by Virdi (2016) was utilised. This plug-in, further to the modified vehicle parameters, applied a novel car following model that enabled platooning and near instantaneous reaction times considering CAV to CAV interactions.

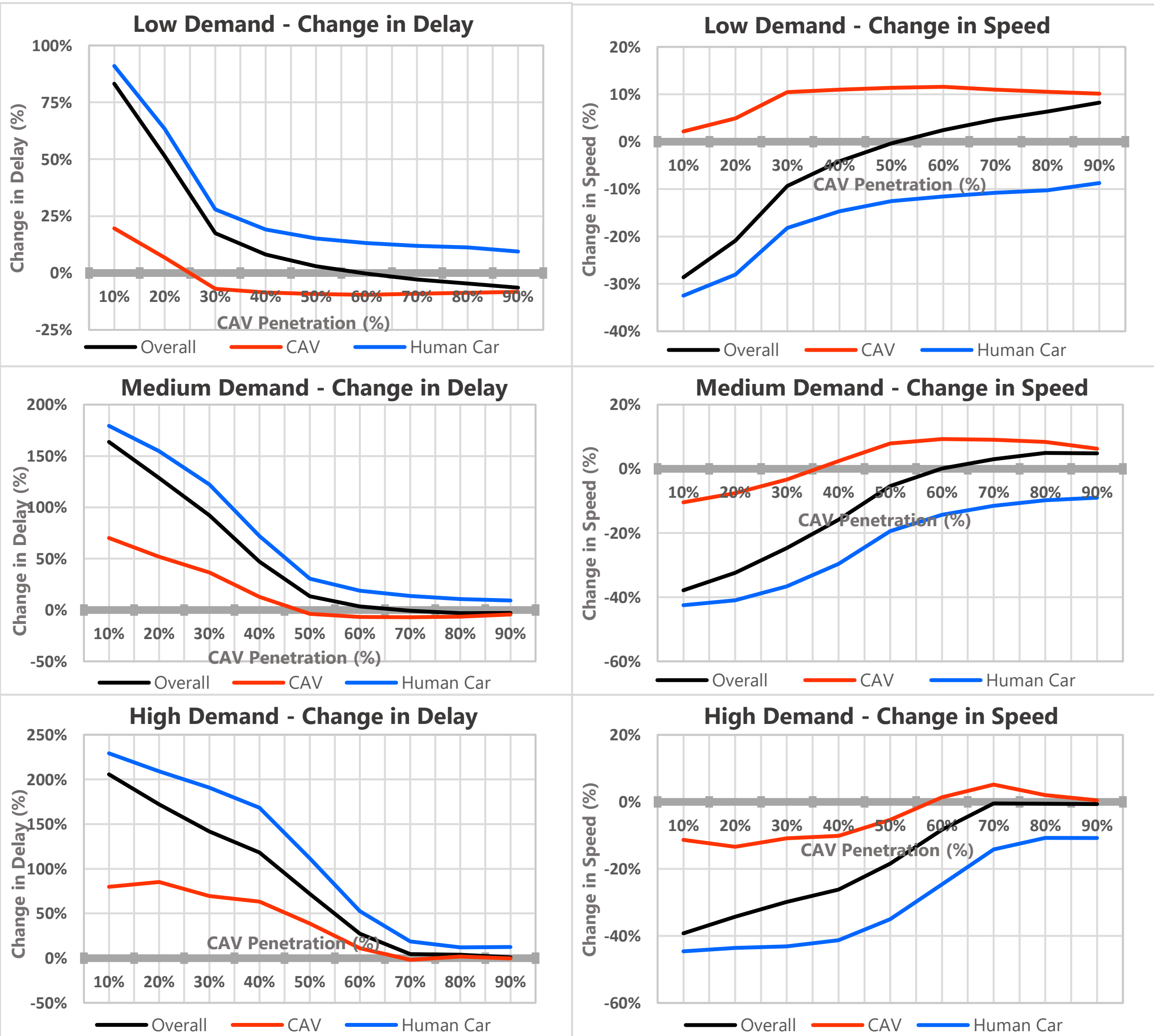
4. Results

The Aimsun microsimulation software reports on a number of network wide performance measures. Average Delay Time (Delay) is the difference between the time actually taken for a vehicle to complete its journey in the model, versus, the time it would have taken under ideal, free flow conditions where no other traffic would be present to increase the travel time of the vehicle. Thus, a reduction in Delay can indicate the network is operating with improved performance, more representative of the ideal performance of the network. Average (Speed) is the average speed of all vehicles in the simulation and can indicate the level of congestion in the network, where a decrease in congestion would correspond to increased speed. The results presented in the following subsections contrast the change in delay and speed for CAVs and human driven vehicles as a result of implementing the redesigns for a number of different CAV penetration percentages. Thus, at each CAV penetration level, the microsimulation software was used to calculate and compare the delay and speed of the network after implementing the redesigns versus before implementation.

4.1 Urban grid model

Figure 3 shows the results for the urban grid model in terms of change in delay and speed as a result of implementing the redesign, for each of the three travel demand scenarios.

Figure 3: Urban Grid Model Results

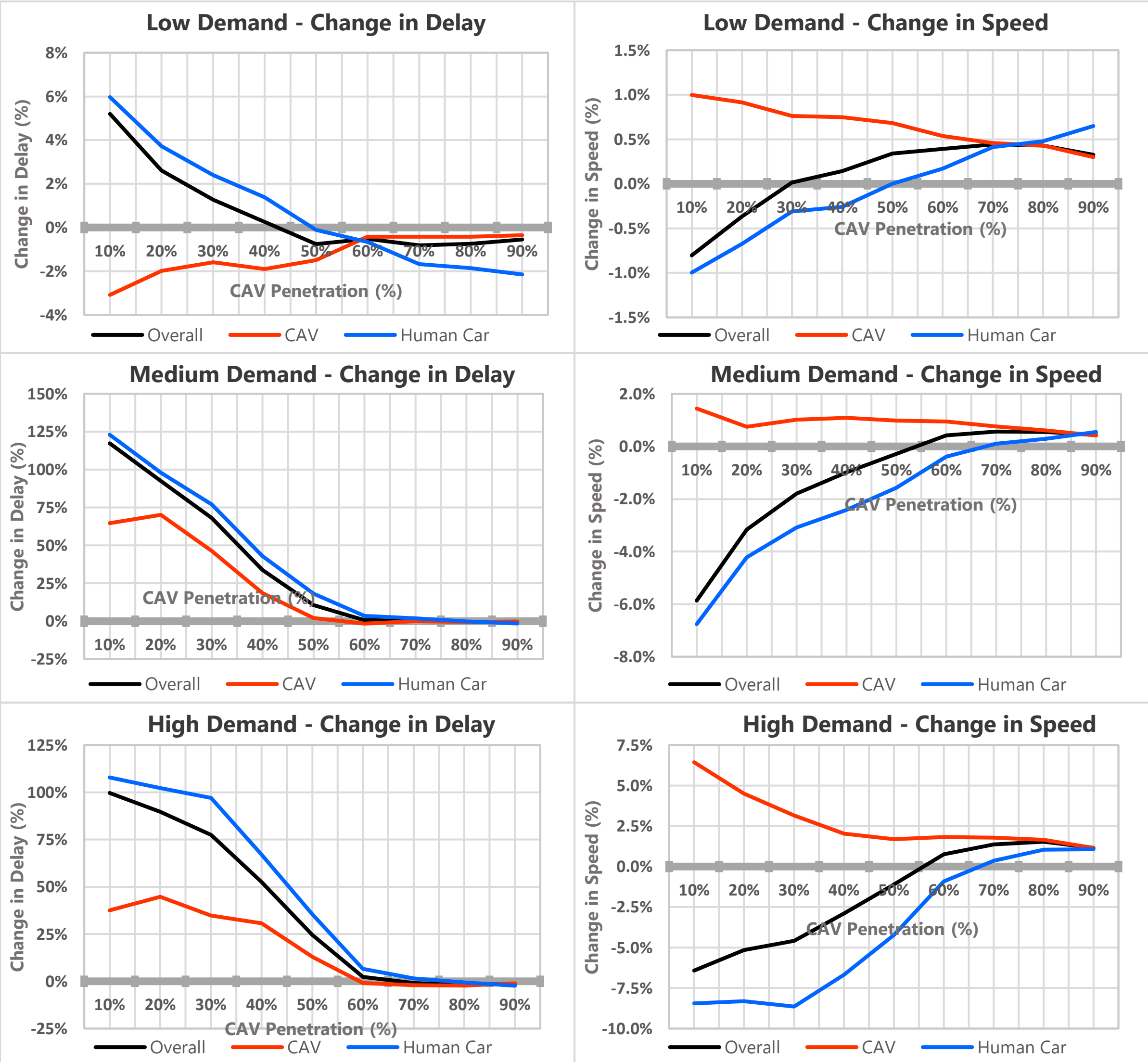


As shown in Figure 3, the introduction of the redesigns at low CAV penetration levels results in significant deteriorations in the performance of the network, with the high demand scenario showing an increase in delay of over 200 percent. Despite this, all demand levels showed that as CAV penetration increases, the implementation of the redesigns can have positive impacts on the delay and speed performance of the network. Furthermore, the higher demand scenarios were generally more sensitive to the initial negative impacts of the redesign, while the lower demand scenario recorded more significant benefits as a result of the redesigns.

4.2 Arterial/ freeway model

Figure 4 shows the results for the arterial/ freeway model in terms of change in delay and speed as a result of implementing the redesign, for each of the three demand scenarios.

Figure 4: Arterial/ Freeway Model Results



Similar to Figure 3, Figure 4 also shown an initially significant deterioration in the performance of the network. However, all demand scenarios show increasing penetration of CAVs resulting in positive impacts on the delay and speed performance of the network.

Furthermore, the higher demand scenarios were also more sensitive to the initial negative impacts of the redesigns.

5. Discussion

Both the CAV-only roads and CAV-only lane redesign options showed merit in being able to improve network wide performance. However, it is important to note that this improvement in network wide performance was found to be highly dependent on the travel demand scenario and the CAV penetration percentages. Significant worsening of network performance were observed due to the redesigns where implemented in unsuitable scenarios. This highlights the need to carry out careful and accurate assessment of the impacts of the redesigns before implementation to ensure that they have a positive impact on the network.

Both models showed a strong pattern of deterioration of network wide performance when the redesigns were enacted for low CAV penetration percentages. However, as the CAV percentage increased, performance benefits appeared. The penetration rate at which the costs and benefits balanced is defined as the “Critical CAV Penetration Percentage”. A penetration rate greater than this value yielded positive outcomes for the network. However, the occurrence of the critical point was observed to vary significantly based on the travel demand scenario – with a general trend for higher travel demands requiring higher critical CAV penetration percentages.

Table 3: Critical CAV Penetration Percentages for Improvement in Network Wide Performance

Network Performance Measure	Urban Grid Model			Arterial/ Freeway Model		
	Low	Med	High	Low	Med	High
Avg. Delay	61%	68%	*	40%	76%	67%
Avg. Speed	50%	60%	70%	30%	54%	56%

***** Improvement not observed for any CAV Penetration Percentage

From the results outlined in Table 3, it is clear that the critical CAV penetration percentage generally occurs between 50 and 70 percent CAV penetration for both models. Thus, implementing the redesigns before a CAV penetration of at least 50 percent is achieved is likely to worsen network performance on arterial roads, freeways and urban traffic environments.

While all scenarios showed an eventual improvement in network wide performance, generally between 50 and 70 percent CAV penetration, CAVs experienced an overall improvement in their performance much earlier than this, as shown in Table 4.

Table 4: Critical CAV Penetration Percentages for Improvement in CAV only Performance

Network Performance Measure	Urban Grid Model			Arterial/ Freeway Model		
	Low	Med	High	Low	Med	High
Avg. Delay	25%	47%	68%	10%	55%	59%
Avg. Speed	10%	36%	58%	10%	10%	10%

Note: 10% Critical CAV Penetration Percentage indicated that all modelled CAV Penetration Percentages recorded an improvement in the given network performance measure

From comparison of Tables 3 and 4, in addition to the results section, it is clear that the performance of CAVs has the potential to be significantly improved by the implementation of the redesign options. Furthermore, this improvement in CAV performance is observed to often occur at CAV penetration percentages far lower than those observed for the total network. This implies that enacting redesigns at an early stage in the adoption of CAVs could significantly improve CAV performance within the network. However, this improvement is likely to result in worsened performance for the non-autonomous users of the network and will most likely correspond to worsened network wide performance.

While the implementation of both redesign options clearly showed the ability to improve performance for CAVs and the overall network, the redesigns were also observed to result in significant deteriorations in performance for non-autonomous vehicles in a number of scenarios. The Urban Grid model showed non-autonomous vehicles performance deteriorating in all scenarios. This was in contrast to the Arterial/Freeway Model, which showed the ability for the redesigns to also result in an improvement in non-autonomous vehicle performance alongside CAVs. In fact, in this model's low and medium travel demand scenarios at high CAV penetration percentages, improvements in non-autonomous vehicle performance were actually found to surpass the improvements in CAV traffic. It is important to note that this does not mean that non-autonomous vehicles recorded improved performance in comparison to CAVs, but only that non-autonomous vehicles benefited to a greater degree from the implementation of the redesigns in comparison to CAVs.

This improvement in non-autonomous vehicle performance as a result of the redesigns can partly be attributed to the fact that on a roadway with adequate spare capacity, a certain proportion of human drivers tend to travel at speeds greater than the speed limit of the roadway, while CAVs are modelled not to have the capability to exceed the legal speed limit. This ability for human drivers to exceed the speed limit is further enhanced through the redesigns separating speed limit abiding CAVs from the non-abiding human driven vehicles.

Furthermore, the reason that non-autonomous vehicles were not able to record an improvement in the Urban Grid Model is likely due to the fact that the redesign of the network forbids them from using a possible total of 98 links to 62, a reduction of 37%. This causes a large number of non-autonomous vehicles to have to pick an alternative route between its origin and destination, which is often a longer route than the previous shortest route. Similarly, CAV only lanes also inconvenience non-autonomous vehicles due to restricting them to travelling on only two of three traffic lanes, which experience greater congestion levels. However, unlike CAV-only road links, it does not restrict non-autonomous vehicles from travelling on an entire roadway and thus does not force them to alter their travel route choice from their shortest path.

The microsimulation approach chosen was selected for its potential to allow simulation of CAVs in a realistic manner. Despite this, shortcomings of the chosen approach include that while it accounts for the advanced car following and reaction times of CAVs, other smart driving behaviour, such as co-ordinated lane changing and merging, have not been represented. Additionally, it is possible that human drivers, pedestrians and cyclists may take advantage of the defensive driving behaviour of CAVs in a phenomenon known as CAV 'bullying' (MIT Technology Review 2016). This behaviour has also not been represented within the microsimulation.

6. Conclusions

Redesigning roadway infrastructure to facilitate the sharing of roadways between autonomous and non-autonomous vehicles needs to be considered carefully to achieve a sustainable road traffic environment and maximise the benefits which can be obtained from the introduction of autonomous vehicles. A number of studies have examined the impacts of infrastructure modifications on roadway operations. This study selected two redesign options and tested these options on two real world inspired microsimulation models, focusing on the relationships between different factors such as autonomous vehicle penetration and travel demand on the effectiveness of the redesign options. The first model included restricting a number of roads for autonomous vehicle only usage on an urban grid network while the second included restricting the third lane on an arterial road and freeway as an autonomous vehicle only lane. The redesigns created a degree of separation between the two vehicle types, enabling improved driving for autonomous vehicles such as platooning and quicker reaction times.

Both models showed that implementation of the redesigns at low autonomous vehicle penetration levels can be a significant detriment to the performance of the network. Eventually, the majority of scenarios resulted in improved performance when autonomous vehicles represented above a certain percentage of total traffic. This tended to be between 50 and 70 percent penetration for the majority of scenarios, however, benefits were observed at significantly lower penetrations for autonomous vehicle traffic only. Furthermore, the arterial/ freeway network showed that despite the reduction in overall network performance, autonomous vehicles were almost always able to still improve their performance as a result of the implementation of the redesigns. Moreover, while the urban grid model showed that non-autonomous vehicles saw a reduction in performance due the redesigns in all scenarios, the arterial/ freeway model showed that non-autonomous vehicles were also able to benefit from the redesigns and even saw a greater improvement in performance than that observed for autonomous vehicles in some scenarios. These results signalled that redesigning of roadways to provide a degree of partial separation between autonomous and non-autonomous vehicles has merit when implemented with respect to autonomous vehicle penetration and travel demand levels.

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