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A safety assessment of mixed fleets with Connected and Autonomous Vehicles using the Surrogate Safety Assessment Module

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ABSTRACT

The transportation network can provide additional utility by addressing the safety concerns on roads. On-road fatalities are an unfortunate loss of life and lead to significant costs for society and the economy. Connected and Autonomous Vehicles (CAVs), envisaged as operating with idealised safety and cooperation, could be a means of mitigating these costs. This paper intends to provide insights into the safety improvements to be attained by incrementally transitioning the fleet to CAVs. This investigation is done by constructing a calibrated microsimulation environment in Vissim and deploying the custom developed Virdi CAV Control Protocol (VCCP) algorithm for CAV behaviour. The CAV behaviour is implemented using an application programming interface and a dynamic linking library. CAVs are introduced to the environment in 10% increments, and safety performance is assessed using the Surrogate Safety Assessment Module (SSAM). The results of this study show that CAVs at low penetrations result in an increase in conflicts at signalised intersections but a decrease at priority-controlled intersections. The initial 20% penetration of CAVs is accompanied by a +22%, −87%, −62% and +33% change in conflicts at the signalised, priority, roundabout and DDI intersection respectively. CAVs at high penetrations indicate a global reduction in conflicts. A 90% CAV penetration is accompanied by a −48%, −100%, −98% and −81% change in conflicts at the signalised, priority, roundabout and DDI intersection respectively.

1. Introduction

Safety in transport has been at the forefront of technological design, innovation and regulation. The New South Wales (NSW) state government of Australia is one of many regulatory bodies that is focused on delivering a safer and more efficient road network. Through its “Towards Zero” initiative, the NSW state government aims to implement strategic and emerging technology to reduce the number of deaths and severe injuries on the road network (Transport for New South Wales, 2018).

Accidents on roads are highly correlated with driving behaviours such as jerk (Anurag et al., 2017) and perception of risk and reward (Dixit, 2013), as well as with the real-time state of the network such as density (Alsalhi et al., 2018). The Australian Bureau of Statistics (ABS) and Transport for New South Wales (TfNSW) (Transport for New South Wales, 2015) indicates that the number of accidents caused by negligent behaviours such as driving under the influence, fatigue and speeding contributes around 30% to the total number of accidents. These accidents are a small subset of the negligent behaviour conducted by motorists, and so to say that CAV technology will mitigate 30% of accidents is an initial and conservative estimate. An independent study conducted by PricewaterhouseCoopers (PwC) indicated that this reduction could be as high as 90% (PricewaterhouseCoopers, 2013).

Significant economic benefits accompany the safety benefits of CAV technology. Road accidents result in a substantial financial cost to society, as was shown by the Bureau of Infrastructure, Transport and Regional Economics (BITRE) in their 2006 inquiry into the financial implications of vehicular accidents (Bureau of Infrastructure, Transport and Regional Economics, 2006). The inquiry concluded that deaths and accidents on the road cost the community approximately AUD$2.8 Billion per year. That is AUD$3,180,598 from each fatality, AUD $346,869 from each serious injury and AUD$17,511 from each minor injury. The breakdown of the costs indicates that post-accident vehicle repair and output losses (the loss to society due to sudden death)

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contribute to over half the costs incurred through an accident. Mainstream CAV technology has the potential to reduce accidents and associated costs significantly.

When an assessment is made from either a financial and economic perspective or a societal impact perspective, potential safety improvements through CAV technology builds a strong business case for this emerging technology. This paper aims to investigate further the effects on road safety resulting from CAV uptake using a microsimulation modelling approach. The selected case study is the Geelong area in Victoria, Australia. The novelty of this research lies in its use of a custom developed CAV control algorithm that focuses on altruistic co-operation, safety and transfer of information. Another contribution is the assessment of CAV safety in a microsimulation environment consisting of both motorways and conventional intersections using the modelling framework.

The remainder of this paper is as follows. Section 2 contains a summation of the literature and work completed to date. Section 3 introduces the framework used for this experimentation. Section 4 describes in greater detail the Virdi CAV Control Protocol (VCCP) algorithm and logic used to emulate CAV behaviour. Section 5 discusses the development of the microsimulation network. Section 6 contains a summation of the results attained through the study. Section 7 contains a discussion of the results and conclusions drawn from the study. Finally, the paper concludes with Section 8, which contains a summation and conclusion of this work.

2. Background

Knowledge regarding the safety implications of CAVs derived from microsimulation modelling is limited. Physical CAV components are rigorously tested during development to minimise component and vehicle failure. Testing CAVs in network settings is difficult due to the requirement of expensive resources and the ethical uncertainties of human involvement in the trial of emerging technology. This ethical uncertainty applies to both the field and simulative testing of co-operative operations. Outlined in this section are the safety studies that have been conducted regarding current practices that inform design today, as well as investigations into the safety impacts of CAV implementation. Also, this section in brief outlines crash-prediction models that have been calibrated using observed data. These models provide insights into the geometric factors that affect human driving safety, provoking thought into whether the same factors will influence a CAV.

2.1. Safety studies of manually driven vehicles

The roundabout has been a staple of network design since the 1950s in many developed countries. Its relatively cheap construction costs, low maintenance and priority-controlled operation, make it a great fit in low flow and low-velocity environments. Vehicle trajectories are forced through a narrow path in a circular motion, with conflicting vehicles required to yield. A study in Victoria, Australia (Ausroads, 1993) measured the casualty rates at 73 intersections before and after the installation of roundabouts. Before installation, these intersections were either give way, stop or police controlled. Post installation, the study found a 74% reduction in casualty rates, a 32% reduction in property damage and a 68% reduction in pedestrian casualty.

Kim and Choi (2013) found that the likelihood of accidents could be predicted using a model dependant on the number of approaches, number of entry lanes, entry width, flare width, number of circulating lanes and circulating lane width. Their study indicated that speed was not a significant contributor to the rate of accidents because roundabouts generally act as pinch points, wherein they force deceleration to 50% of free flow speeds as vehicles travel through them.

Qin et al. (2011) also aimed to create a negative binomial crash prediction model using data for roundabouts obtained in Wisconsin. Their approach involved developing a range of models with dependent variables that included Annual Average Daily Traffic (AADT), number of legs, number of lanes, geographic location in Wisconsin, the configuration of the yield signage, inscribed circle diameter and outer circle diameter. The model which considered the geographic location of the roundabout best fit the observed data. This study demonstrated that the familiarity of the driver to the concept and operation of a roundabout was more influential to its safety performance than the geometric considerations given to its inner and outer diameters or other design elements

Turner and Roozenburg (2006) used data from 104 roundabouts in New Zealand to develop a range of accident prediction models to describe the likelihood of accidents in certain situations empirically. The models estimate the likelihood of accidents for situations such as entering and circulating vehicles, rear-end collisions, loss-of-control accidents, pedestrians, cyclists and high-velocity roundabouts. Contrary to other accident prediction models, their study found that speed and flow play a more significant role in the occurrences of accidents in motor vehicles than the geometric design does. Their model suggests that if the mean circulating velocity of 20 km/h were increased by 20%, then the resulting number of accidents would increase by 38%.

Contrary to priority-controlled intersections, the signalised intersection operates by dictating right of way and minimising concurrent conflicting movement. However, this style of operation introduces the motorist to the “dilemma zone” (Papaioannou, 2007). The “dilemma zone” is the amber light period where a driver must decide whether to break in preparation of the red light or proceed through the intersection. Papaioannou found that the factors affecting this decision included pavement condition, intersection layout, cycle length, position in a platoon and vehicle speed. The study concluded that in a 60 km/h zone, 26.3% of drivers exceeded the speed limit to cross the intersection in the “dilemma zone”. Males on average are 14 times more likely to exceed the speed limit and pass through the intersection on an amber light, with the 85% percentile exceeding the speed limit by 26%. The compliant behaviour of CAVs may eliminate dangerous behaviour such as this.

The diverging diamond intersection (DDI) was first implemented in the United States in 2009 and has gained popularity in recent times. The operation of a DDI involves the traffic stream momentarily crossing to the opposing side before they return to the correct side at another crossing point downstream. This configuration intends to reduce the number of conflicting movements that are present in conventional diamond intersections. This intersection configuration yields higher throughput, contains fewer conflict points and is designed to be safer.

Claros et al. (2015) measured the change in the frequency of accidents in six locations in Missouri before and after the implementation of a DDI. This study found substantial reductions in the occurrences of accidents for all severity types. Fatal crashes showed a 59.3%–63.2% reduction, property damage crashes showed a 33.9%–44.8% reduction and total crashes showed a 40.8%–47.9% reduction. A comparable study conducted by Hummer et al. (2016) using a similar methodology found supporting results. Their study found that the replacement of conventional intersections with DDIs resulted in an overall crash reduction of 33%.

The variance in the explanatory variables used in these crash prediction models makes it difficult to predict the effect of CAVs on intersection safety. On the one hand, models such as that presented by Qin et al. place a heavy emphasis on the importance of geometric design in roundabout safety, other models such as that by Turner and Roozenburg focus on the flow and speed of vehicles. CAVs are expected to traverse the network in platoons with significantly smaller headways and higher average speeds. The Turner and Roozenburg models imply that the likelihood of accidents has the potential to increase in the interim scenarios, as portions of the network begin to transition to autonomous. Similarly, the notion of the ‘dilemma zone’, though pertinent to motorists occupying the road today, is antiquated for a vehicle whose behaviour is governed by a set of deterministic algorithms. For this reason, a framework such as that used in this paper for evaluating CAV safety is necessary. This framework, outlined in Section 3, is capable of qualitatively evaluating CAV safety by determining the likelihood of conflicts. The economic impact of CAVs through safety improvements can then be determined.

2.2. Safety studies of autonomously driven vehicles

Mentioned prior, assessing CAV safety is necessary for evaluating their societal and economic impact. Studies of this nature may accelerate the development of political and legal policies required to facilitate their adoption. However, such studies are sparse. Outlined in this section are recent investigations in the safety implications of CAVs.

Carbaugh et al. (1998) aimed to assess the severity and frequency of rear-end collisions for automated and manual highway systems. Their modelling found that in their testbed, a typical manual driver has a probability of collision of 0.87, whereas an alert manual driver has a probability of collision of 0.11. The CAVs, on the other hand, were found to have a probability of collision of 0.028. They were also expected to collide at less than 30% the velocity of typical manual drivers. This study indicated that CAVs are four times safer than manual drivers. The testbed was confined to the highway environment, assessing the safety implications of transverse vehicle interactions. Also, their study used probabilistic models to identify conflicts between vehicles. The novelty of this work, however, is in its use of microsimulation modelling to emulate CAV behaviour for each agent. The evaluation of safety is conducted via analysis of vehicle trajectories in forecasting position and identifying potential conflicts.

Tibljaš et al. (2018) also aimed to quantify CAV safety, using a microsimulation environment. CAV behaviour was emulated by changing the parameters of the Wiedemann 99 model (PTV Group, 2016), and safety performance was assessed using the Surrogate Safety Assessment Module (SSAM). Their assessment concluded that the number of conflicts would increase with the introduction of CAVs. While both our study and the study of Tibljas et al. use microsimulation with Vissim and the SSAM module for safety evaluation, the novelty of this work lies in its use of a custom and external control protocol for dictating CAV behaviour. Tibljas et al. adjusted the parameters of the default car-following model used by the microsimulation software. More refined results can be obtained using a framework that has been developed specifically for CAVs, giving special attention to CAV behaviour.

Rahman and Abdel-Aty (2018) used the Vissim commercial microsimulator and SSAM in their analysis of the effects of CAV behaviour on safety. Their study used a calibrated model of the Holland East-West Expressway (SR408) in Orlando, Florida as the testbed, and the Intelligent Driver Model to emulate the behaviour of CAVs. Their study used five surrogate metrics to assess safety; the standard deviation of speed, time exposed time-to-collision (TET), time-integrated time-to-collision (TIT), time exposed rear-end crash risk index (TERCRI), and sideswipe crash risk (SSCR). Their study showed a reduction in TIT and TET of between 19%–21% when CAVs were allowed to form platoons in all lanes, and a reduction of between 26%–28% in the managed lanes scenarios. Our study uses a similar methodology, however, employs a different CAV car following model and aims to extend the findings by also investigating the effects on safety at varying intersections as opposed to solely on motorway segments.

Kinando et al. (2018) used the 2017 crash data obtained from the Signal Four Analytics website maintained by the University of Florida; to qualitatively assess the likelihood of accidents. The crash data indicated that for this segment, 85.1% of accidents were at intersections, with the remaining 14.9% occurring on the freeway segment. The rear-end collisions accounted for 55% of all collisions. By qualitatively assessing each accident type and determining whether CAV operation and technology will be adequate in eliminating it, Kidando et al. concluded that the potential reduction in conflicts resulting from CAV operation is between 17% and 70%. Our study aims to use microsimulation modelling and a custom CAV control algorithm to assess safety as opposed to a qualitative analysis of historical crash data.

Rahman et al. (2018) attempted to investigate the impact of CAV operation on safety during reduced visibility conditions such as fog. They used the Interstate I-4 in Florida as the basis of their base model, the IDM car following model for CAV behaviour and the Vissim commercial microsimulator for modelling vehicle interaction. Their study used the standard deviation of speed, the standard deviation of headway and the rear-end crash risk index (RCRI) as surrogate measures of safety. The "look ahead" parameter of the commercial software was considered most critical for calibrating to fog conditions. Also, the ten parameters of the car following model were also iteratively adjusted to find the best match between observed and modelled car following during fog conditions. The modelling found the most significant improvement at a CAV penetration of 100%, with significant decreases seen after 30% penetration. The limitation of this study was in its constraint of the assessment to the highway environment. Our study aims to extend the understanding of CAV safety by conducting simulations of mixed urban and freeway settings.

As data becomes available regarding CAV operation, these models can be better calibrated. The California Department of Motor Vehicles (DMV) requires that disengagement and accident data be made public by CAV developers, in exchange for permits to operate the vehicles (S. o. California, 2019). A study into the 2015 data released by manufacturers (Dixit et al., 2016) assessed several metrics, including the trust placed in CAVs by the occupants. This study was done by evaluating the degree of correlation between autonomous disengagements and manual disengagements. An autonomous disengagement is an event where the occupant is required to take control of the vehicle due to a shortcoming or error on the CAVs behalf. A manual disengagement is an event where the occupant willingly seizes control of the CAV. The study found that there was a high correlation (0.73) between the frequency of autonomous disengagements and manual disengagements, indicating that trust in this emerging technology is currently fickle, with further real world and microsimulation testing being necessary to develop a complete picture regarding CAV safety. Studies such as this that evaluate the safety impacts of emerging technology help build confidence in its potential. They comfort consumers and promote the adoption of new technology.

3. Framework

The framework used in this study is responsible for using traffic and network data to emulate CAVs in a microsimulation environment. During simulation, the microsimulator records trajectory data. The SSAM module then uses this data to highlight potential conflicts that arose during runtime. Outlined in Fig. 1 is the data flow structure of this study, with a more detailed explanation of each component provided in this section. Its four components can highlight the framework. The data (coloured in blue) is used to provide an element of realism to the testing. This data acts as spatial and behavioural constraints for vehicle operation. The microsimulator (coloured in grey) is used to emulate vehicle interactions based on the restrictions imposed by the network and traffic data. The microsimulator is also responsible for generating, recording and forwarding data to both the external control algorithm and analysis platform. The VCCP algorithm (coloured in orange) is responsible for dictating CAV movement. The Microsimulator passes geospatial and behavioural information about the vehicle to the external control algorithm, where this information is used to determine appropriate acceleration and lane change decision. The analysis platform (coloured in green) processes the data produced by the microsimulator.

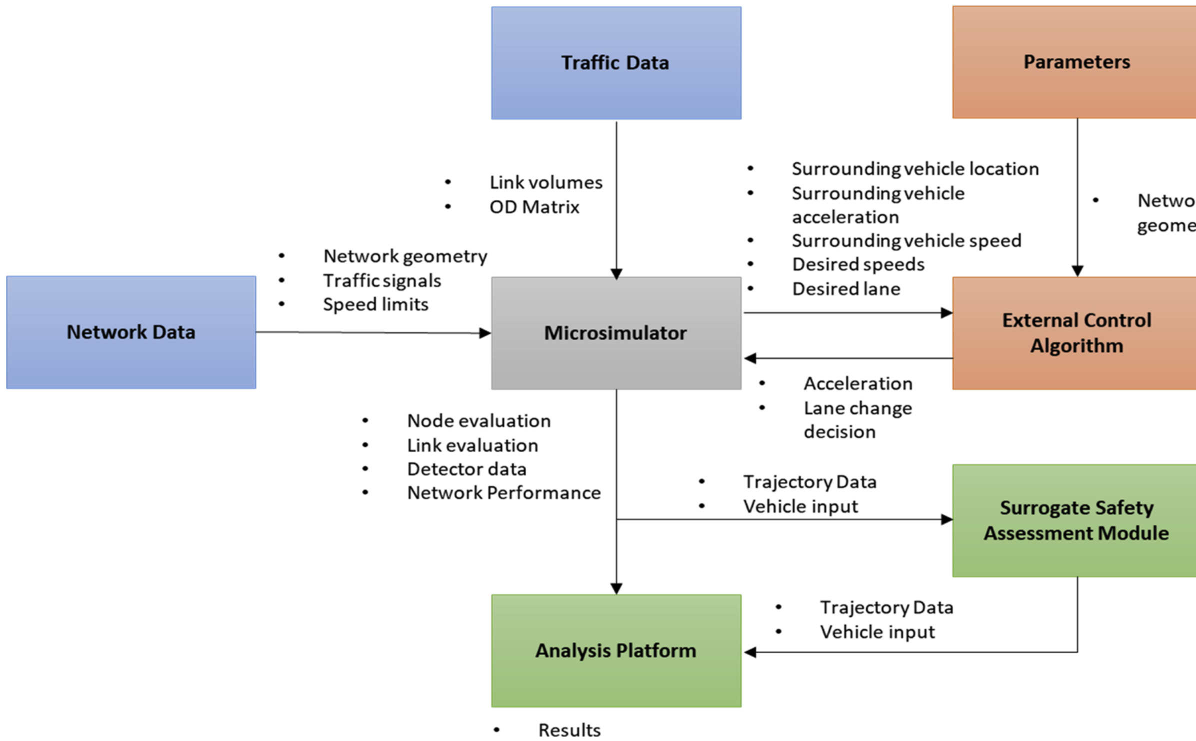


Fig. 1. Framework for the flow of data.

3.1. Traffic data

The traffic data contains volume along links and characteristic 24 -h traffic profile data. The volume along links from public sources is available as annual average daily traffic and is converted to typical peak hour volumes using the characteristic profiles. This data is then used to calibrate an origin-destination matrix manually. This process ensures a well calibrated and fit for purpose base traffic model.

3.2. Network data

Google Maps, Bing Maps and OpenStreetMap are used to obtain the network data. Using the Satellite capabilities of Bing Maps and OpenStreetMap, these platforms form an underlay used in creating the network geometry, ensuring correct road alignment and number of lanes. The Street-View capabilities of Google Maps are used to determine the signal phasing configuration. Cycle durations are set using the Roads and Maritime Services signalling guidelines (Roads and Maritime Services, 2016).

3.3. Microsimulator

This study uses commercial microsimulation software (Vissim 9-09) (PTV Group, 2016). The purpose of the microsimulator is to provide an environment in which the agents obtained from the traffic data can interact with each other. The interactions are confined in scope by restrictions imposed by the network data.

The default Wiedemann models used by the simulator are used to control human vehicle behaviour. The urban settings use the Wiedemann 74 model, and the freeway settings use the Wiedemann 99. These models differ in the way they facilitate lane changing, with the Wiedemann 74 model being more cooperative and facilitate lane changes with greater ease. This model is a “psycho-physical perception model”. This term describes both the psychological and physical factors that affect human acceleration calculation. The psychological input is the speed difference between the current and lead vehicle, and the physical input is the current speed and headway to the leader. The model subdivides the car following behaviour of a driver into four categories; they are as follows:

- Free Driving: In this state, the drive aims to maximise its travel speed. The preceding vehicle does not affect the behaviour of the current vehicle.
- Approaching: This state arises when a vehicle approaches a driver with a lower speed. Deceleration is set to result in no difference in speed between the current and lead vehicle when the driver has reached the safe following distance.
- Following: In this state, the vehicle follows the lead vehicle without decelerating or accelerating. The safe following distance is kept constant. This behaviour would be akin to the platooning behaviour of CAVs. However, this state is not stable. It is only maintained when the lead vehicle has a lower desired velocity than the follower, but the follower is still travelling with speed within its tolerance and does not conduct a discretionary lane change.
- Braking: This state arises when the distance to the preceding vehicle falls below safe. The vehicle applies a medium to heavy deceleration to recreate a safe following distance. This situation arises if the lead vehicle abruptly changes behaviour or if an adjacent vehicle changes lane in front.

In addition to controlling human vehicle behaviour, the microsimulator is responsible for generating, storing or forwarding real-time data. The microsimulator provides real-time information including vehicle positions, current behaviour and future intentions to the VCCP algorithm. The algorithm then uses this information to determine the appropriate course of action and provide back to the microsimulator the acceleration and lane change intentions of the vehicle for the next time increment.

3.4. CAV behavioural control

The VCCP algorithm is used to dictate CAV behaviour. The microsimulator provides real-time data to the algorithm, which then addresses three components of the CAV behaviour, car following, lane changing and gap acceptance. This data exchange occurs during each time increment for each vehicle. Explanation of the algorithm is provided in detail in Section 4. The VCCP algorithm is developed in C++ using the Vissim application programming interface and incorporated into the microsimulator using a dynamic linking library.

3.5. Parameters

To take better advantage of vehicle-to-vehicle and vehicle-to-infrastructure capabilities, the CAVs should be aware of obstacles in their path well before a human driver would be. The parameters module fulfils this role by storing and providing the external control algorithm with information regarding upcoming obstructions in the CAVs path. This information allows the CAV to change lanes promptly, turning what would otherwise be a mandatory lane change downstream into a discretionary lane change upstream. The purpose of this is to reduce imprudent and disruptive lane changing that occurs near obstacles, reducing the number of braking shockwaves that surface in the target lane.

3.6. Surrogate Safety Assessment Module

SSAM (Pu and Joshi, 2008) is a tool created by Siemens Energy and Automation, Inc. with the Federal Highway Administration. This tool uses the trajectory data generated by microsimulators to identify potential conflicts, based on the definition of a conflict provided by the modeller.

A trajectory file is created by the microsimulator during model runtime and contains information about the position and movement of each vehicle. Data in the trajectory file forms a subset of either the "Dimension", "Timestep" or "Vehicle" class.

- The "Dimension" class contains information regarding the spatial characteristics of the observation area. "MinX", "MinY", "MaxX" and "MaxY" are used to define the rectangular bounding box of the microsimulation environment.
- The "Timestep" class contains a recording of the current time step since the commencement of the simulation. This variable allows SSAM to position the vehicles temporally.
- Finally, the "Vehicle" class contains information about the spatial characteristics of the vehicle. "VehicleID", "Link ID", "Lane ID", "Front X", "Front Y", "Rear X" and "Rear Y" are used to position the vehicle spatially. "Speed" and "Acceleration" are used to forecast the movement of the vehicle. Using the temporal and spatial information, SSAM determines whether the trajectory of the vehicle will interact with that of another, and reports information regarding this interaction. This information includes time to conflict, speed during conflict and speed after conflict.

SSAM provides a range of criteria by which to define a collision. Maximum time-to-collision (TTC) is estimated based on the current location, speed and trajectory of the two vehicles involved in the interaction. Maximum post-encroachment-time (PET) is the time between when the proceeding vehicle last occupied the space that the following vehicle is occupying.

The rear end angle and the crossing angle are also used to identify potential conflicts. The rear end angle is used to define a potential collision during car following and lane changing. The crossing angle defines potential collisions in head-on scenarios, such as during manoeuvres through an intersection. Fig. 2 provides a diagrammatical representation of these angles.

Due to the small headway kept between CAVs, SSAM tends to flag safe interactions for CAVs as a potential conflict. Also, consider the situation depicted in Fig. 3, where a vehicle is changing lanes in a congested environment but is forced to remain in the centreline between both lanes due to spatial restrictions. In the microsimulator, once the front bumper of the vehicle has entered the adjacent lane, the following vehicles will no longer consider this vehicle as a leader and progress to seemingly drive through its rear. However, SSAM uses both the front and rear coordinates and flags these interactions as conflicts.

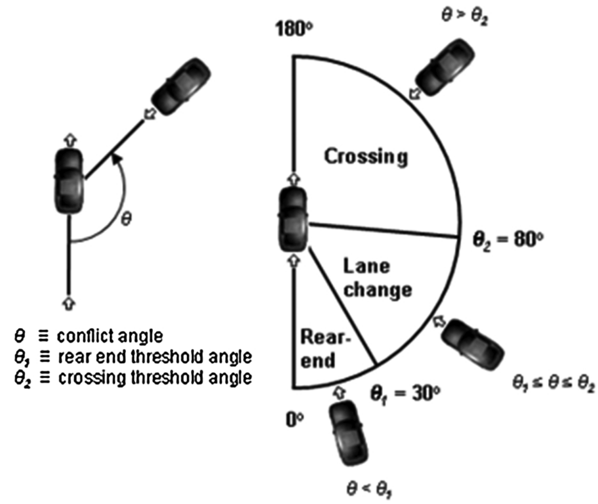


Fig. 2. Diagrammatical representation of the rear end angle and the crossing angle. (Source: (Pu and Joshi, 2008)).

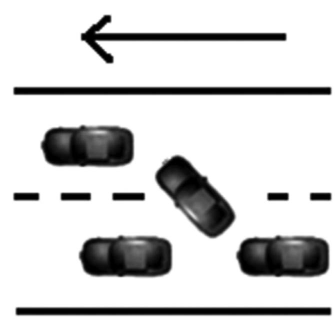


Fig. 3. A scenario in which SSAM may inaccurately identify a conflict for CAVs.

3.7. Analysis platform

The analysis platform is responsible for processing the raw data obtained from the microsimulator and SSAM. The data from the microsimulator and SSAM include:

- Node evaluation results - contain information regarding the performance of intersections by tracking the movement of vehicles through the node. This information can be used to infer volume, density, speed and delay.
- Link evaluation results - provide similar information, but along links and for midblock locations.
- Detector data - can be collected at any point in the network and is used to attain velocity, acceleration and delay information.
- Network performance data - provides a high-level aggregation of network statistics including total system travel time, total system delay, throughput and volume.
- Trajectory data – contains the geospatial and movement information for each vehicle in the network for each time increment. This information is used to infer potential conflicts.
- Vehicle input data – is used to distinguish between which vehicles in the network are human-driven and which are CAVs. This information is used with the trajectory data to classify the interaction as

either between humans, between CAVs or between a human and a CAV.

4. VCCP algorithm

The VCCP algorithm is responsible for controlling all CAV behaviour, from the moment a CAV enters the network to the moment it leaves. Its responsibility includes evaluating CAV acceleration, lane changing and gap acceptance. The novelty of this modelling approach is that while others in literature have used mathematical models or adjusted software parameters to evaluate CAV safety, this study develops and employs a complete behavioural control algorithm to emulate CAV behaviour. The relaxation of safety constraints on reaction times and following headways applied in the following logic is akin to the vehicles operating with the highest level of autonomy (often denoted as level 4 or level 5 autonomy. This autonomy implies that human intervention is not only not required in vehicle operation, but also is not permitted. This restriction maintains a degree of homogeneity in the CAV behaviour, as they do not revert to human behaviour. A detailed explanation of this algorithm is as follows.

4.1. CAV car Following logic

For the CAVs, the lead vehicle uses an acceleration model developed by Talebpour and Mahmassani (2016) to calculate acceleration, while all following vehicles then reactively adjust their acceleration according to the rule-based algorithm outlined in this section. The Talebpour and Mahmassani acceleration model provided in Eq. (1) is based on acceleration, velocity and headway.

$$a_n(t) = k_a a_{n-1}(t-\tau) + k_v(v_{n-1}(t-\tau) - v_n(t-\tau)) + k_d(s_n(t-\tau) - s_{ref}) \tag{1}$$

Where, $a_n(t)$ and $v_n(t)$ is the acceleration and velocity respectively of vehicle n at time t, k_a, k_v and k_d are model parameters, τ is the simulation time step, s_n is the spacing and s_{ref} is the maximum value between the minimum headway (s_{min}), the following distance based on reaction time and safe following distance.

The purpose of the “k” parameters is to alter CAV behaviour as follows:

- k_a controls the influence of the acceleration of the lead vehicles on the acceleration of the current vehicle. The purpose of this is to reduce jerk (change in acceleration) in response to the changing behaviour of the lead vehicle. A higher k_d results in a greater influence of the lead vehicle.
- k_v controls the influence of the lead vehicles velocity on the current vehicle. Similar to k_a, this parameter reduces sudden changes in velocity, which may occur when the lead vehicle changes behaviour (as in a lane change or merge).
- k_d controls the influence of the headway on the CAVs behaviour, with a higher k_d value resulting in a CAV being more responsive to large headways

These parameters are adjusted in response to changing CAV behaviour, characteristics, technology or capabilities. They are not dependant on the microsimulation environment. For this reason, the same parameters used by the Talebpour and Mahmassani study are retained in this study. However, the minimum car following distance of 0.5 m is used. CAVs are expected to communicate at a rate of 1 communication per 515 μs (Milanes et al., 2012), which is approximately 2000 cycles per second. In the most extreme scenario where the CAVs are operating at full speed in the network, they are travelling at 16.6 m/s at a headway of 0.5 m, resulting in a headway of 0.03 s. For a collision to occur in the worst-case scenario, the lead vehicle would need to stop immediately, and communication would need to experience a packet loss of 60 consecutive packets per second (3%).

The intention of this study is not to asses or validate the claim that packet loss of CAV communication will be less than 3%. A packet loss of 3% seems unreasonably high for the mass deployment of automated vehicles. For this reason, level 4 and level 5 CAV operation is assumed, where human intervention is not possible, nor is it allowed, and the CAV hardware is faultless. Additionally, other studies (Latrech et al., 2018) have used a minimum headway comprised of the standstill distance and a factor of the current travel velocity. This study assumes that a faster moving vehicle does not justify a decrease in safety, only an increase in consequences should an accident occur. When assuming that CAV sensing equipment is faultless, the velocity component of minimum headway becomes redundant, and the minimum following distance can be reduced to the standstill distance.

The acceleration model controls the acceleration of the platoon leaders. The additional contribution of this work lies in its development and use of a behavioural control logic that prioritises platooning, vehicle cooperation and altruism. It works by assigning the current vehicle with a set of real and virtual leaders. The real leader imposes the strictest behavioural constraints to maintain safety. The virtual leaders impose other constraints to facilitate cooperation and altruism in lane changing, with the vehicle attaining an acceleration needed to meet the safety constraints imposed by all real and virtual leaders. The process places the vehicle into one of four circumstances:

- The vehicle intends to remain in the current lane: The lead vehicle is assigned as the immediate leader of the current lane in this case. The behaviour of the vehicle is linked to the behaviour of the leader, with speed, acceleration or deceleration being matched with a one simulation timestep delay. Bounds are placed on vehicle behaviour to prevent erratic changes to behaviour. Bounds on speed are imposed by the network data, acceleration is restricted to between -8 m/s^2 and 6 m/s^2 and jerk is restricted to 0.5 m/s^3. If the current vehicle is the leader of the platoon, then $a_{n-1} = 0$, $v_{n-1} = 0$ and $s_n = \frac{s_{ref}}{t-\tau}$. This results in $a_n(t) = k_v v_{n-1}(t-\tau)$ and acceleration is governed by k_v. The vehicle is not assigned a virtual leader in this case.
- The vehicle intends to change lanes: In this case, the vehicle emits a signal notifying vehicles in the target lane of its intentions to change lanes. The real leader is assigned as the lead vehicle in the current lane, and the virtual leader is assigned as the lead vehicle in the target lane. The acceleration of the vehicle is calculated to each of the real and virtual leaders, with the minimum acceleration adopted. This method ensures that safety constraints imposed by all surrounding vehicles are maintained. In the situation where a vehicle is travelling next to its virtual leader, the acceleration model will impose an extreme deceleration. Such a reaction would not be necessary, which is the justification for restricting the jerk imposed by virtual leaders to 0.5 m/s^3.
- An adjacent vehicle intends to change lanes: In this case, the vehicle is on the receiving end of the signal emitted in the previous case. The vehicle assigns the real leader as the leader of the current lane and the virtual leader as the adjacent vehicle intending to change lanes. Acceleration is calculated similarly to the previous case.
- The trajectory of the vehicle is obstructed: A trajectory obstruction may take the form of a physical element on the road such as another vehicle, or it may be a network geometric element such as a lane drop or a fork in the road. In this case, calculation of acceleration is similar to the preceding cases, with the obstruction assigned as the real leader and the leader of the target lane assigned as the virtual leader. The real leader is given an acceleration of $a_{n-1} = 0$ and velocity of $v_{n-1} = 0$.

This process allows vehicles to actively create appropriate gaps (defined in Section 4.2) for one another, as opposed to the merging

Subroutine
For all agents surrounding Vehicle
get Acceleration; get velocity; get location; get Vehicle Type; get Lane Change Intention; get Length
Condition 1
If (Vehicle does not intend to change lanes)
Set Real Leader as a preceding vehicle in the current lane
Set Virtual Leader as null
If (Real Leader == null)
$a_{n-1} = 0, v_{n-1} = 0$ and $s_n = \frac{s_{ref}}{t-\tau}$.
Acceleration_Real = Talebpour & Mahmassani car-following model with Real Leader
Acceleration_Virtual = infinity
Return min(Acceleration_Real, Acceleration_Virtual)
Condition 2
If (Vehicle desires lane change)
Set Real Leader as a preceding vehicle in the current lane
Set Virtual Leader as preceding vehicle in target lane
Acceleration_Real = Talebpour & Mahmassani car-following model with Real Leader
Acceleration_Virtual = Talebpour & Mahmassani car-following model with Virtual Leader
If (|Acceleration_Virtual – Acceleration| > 0.5)
Acceleration_Virtual = Acceleration – 0.5
Return min(Acceleration_Real, Acceleration_Virtual)
Condition 3
If (Vehicle is facilitating a lane change)
Set Real Leader as a preceding vehicle in the current lane
Set Virtual Leader as vehicle that transmitted lane-change signal
Acceleration_Real = Talebpour & Mahmassani car-following model with Real Leader
Acceleration_Virtual = Talebpour & Mahmassani car-following model with Virtual Leader
If (|Acceleration_Virtual – Acceleration| > 0.5)
Acceleration_Virtual = Acceleration – 0.5
Return min(Acceleration_Real, Acceleration_Virtual)
Condition 4
If (trajectory of vehicle is obstructed)
Set Real Leader as obstruction
Set Virtual Leader as leader in target lane
For Real Leader
$a_{n-1} = 0, v_{n-1} =$
Acceleration_Real = Talebpour & Mahmassani car-following model with Real Leader
Acceleration_Virtual = Talebpour & Mahmassani car-following model with Virtual Leader
If (|Acceleration_Virtual – Acceleration| > 0.5)
Acceleration_Virtual = Acceleration – 0.5
Return min(Acceleration_Real, Acceleration_Virtual)
Set Acceleration = min(Condition 1, Condition 2, Condition 3, Condition 4)

Fig. 4. Pseudocode for the calculation of CAV acceleration.

vehicle decelerating and waiting for a safe gap to surface. Fig. 4 displays this logic in the form of pseudocode.

4.2. Manual vehicle car following logic

The Wiedemann 74 and Wiedemann 99 car following models are used for manual vehicles, as the microsimulator natively uses them. The models are an arrangement of mathematical formulae in a rule-based structure. The mathematical models are used to determine the threshold for different actions in the algorithm and are diagrammatically presented in Fig. 5 (PTV Group, 2016), as well as mathematically (Aghabayk et al., 2013) throughout this section.

The Wiedemann 99 parameters are as follows:

- CC0 Standstill Distance (1.5 m) – the average standstill distance between vehicles. It has no variance
- CC1 Headway Time (0.9 s) – time headway used to calculate the average following distance.
- CC2 Following Variation (4.0 m) – the headway with which the safe following distance is allowed to surpass before the following vehicle accelerates within maximum link speeds.
- CC3 Threshold for Entering Following (−8.00 s) – time taken to reach the safe following distance when a slower lead vehicle is registered
- CC4 Negative Following Threshold (−0.35 m/s) – the sensitivity of the vehicle to the lead vehicles negative changes in velocity.
- CC5 Positive Following Threshold (0.35 m/s) – the sensitivity of the vehicle to the lead vehicles positive changes in velocity
- CC6 Speed Dependency of Oscillation (11.44 m · s) – influence of distance on speed oscillations, with 0 indicating that speed oscillations are independent of distance.
- CC7 Oscillation Acceleration (0.25 m/s2)
- CC8 Standstill Acceleration (3.50 m/s2) – desired acceleration when starting from a standstill, limited by the maximum acceleration
- CC9 Acceleration with 80 km/hr (1.50 m/s2) – desired acceleration at 80 km/hr, limited by the maximum acceleration

These parameters are used to refine behaviour when localised deviations from standard behaviour are observed. However, the base model in this study is performing well below the saturation point and experiences little to no congestion under current conditions; adjustments to these parameters are not warranted. For this reason, the default parameters recommended by the commercial microsimulator and quoted above are adapted for manual vehicles. The regions outline in Fig. 5 and adjusted using the "CC" parameters are calculated as follows.

$$A_x = L + CC0 \quad (2)$$

Where, A_x is the collision threshold and L is the length of the lead

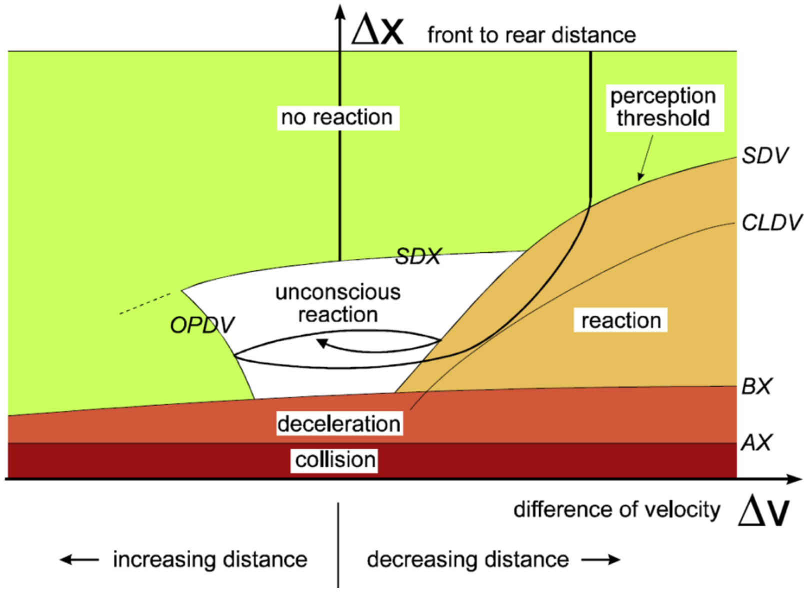


Fig. 5. Thresholds for the Wiedemann 99 car following model (PTV Group, 2016).

vehicle.

$$B_x = A_x + CC1 \times v \quad (3)$$

Where, B_x is the deceleration threshold and v is the velocity of the vehicle if it is slower than the lead vehicle. Otherwise, it is the velocity of the lead vehicle with an error term. The error term is randomly generated between -0.5 and 0.5

$$CLDV = \frac{CC6}{17000} \times (\Delta x - L)^2 - CC4 \quad (4)$$

Where, $CLDV$ is the reaction threshold and Δx is the distance headway between the current and lead vehicle

$$SDV = -\frac{\Delta x - B_x - CC2}{CC3} - CC4 \quad (5)$$

Where, SDV is the Perception threshold.

$$SDX = B_x + CC2 \quad (6)$$

Where, SDX is the unconscious reaction threshold.

$$OPDV = -\frac{CC6}{17000} \times (\Delta x - L)^2 - \delta \cdot CC5 \quad (7)$$

Where, $OPDV$ dictates the upper bound for when unconscious reaction still applies and δ is a dummy variable that is 1 when the subject speed is greater than CC5 and 0 otherwise.

The Wiedemann 74 model used for manual vehicles in the urban setting and the default parameters recommended by the commercial microsimulator are as follows:

- Average Standstill Distance (2.00 m) – defines the average distance between two cars with a deviation of 1.0 m normally distributed around 0 m.
- Additive Part of Safety Distance (2.00) – used in the calculation of the safety distance (explained in Eq. (8))
- Multiplic Part of Safety Distance (3.00) – used in the calculation of the safety distance (explained in Eq. (8))

The safety distance (b) mentioned above is a function of the additive part (b_{add}) and the multiplic part (b_{mult}). The safety distance is calculated as;

$$b = (b_{add} + b_{mult} \times z) \times \sqrt{v} \quad (8)$$

Where z has a range of 0–1, normally distributed around 0.5 with a standard deviation of 0.15 and v is the vehicle velocity (m/s).

4.3. CAV gap acceptance logic

The gap acceptance logic presented in this section applies to CAVs when a vehicle cooperatively conducts a lane change with another vehicle. This logic assumes that vehicle-to-vehicle communication operates without fault and that communication is not hindered, delayed or contains malicious or incorrect information.

The vehicle intending to make the lane change and the follower of the target lane will decelerate until the critical platoon gap is established, which in this study is 0.5 m. The suitability of a target gap is evaluated based on the following two criteria:

- Headway to the leader and follower of the target lane is greater than or equal to the critical gap (0.5 m).
- The velocity of the leader in the target lane is α greater than, and the velocity of the follower in the target lane is β less than, the velocity of the lane changing vehicle, with α and β defined below in Eqs. (9) and (10) respectively.

The first condition is the retention of the minimum headway. Regardless of whether a vehicle can recreate this minimum headway promptly or not, a vehicle will not be permitted to change lanes until this gap is available. The second condition is intended to maintain flow stability and reduce the creation of compression waves in the traffic stream from braking. The likelihood of headways falling below the minimum value is eliminated by ensuring that the velocity of the leader is greater than and the velocity of the follower is less than the lane changing vehicle.

The parameters α and β are a function of the current velocity of the target lane leader and follower. They are calculated to ensure that in the next time increment, the maximum acceleration of the follower or the maximum braking of the leader will not result in a headway that falls below the safe minimum. The velocity of the leader and follower in the next time step, as well as the α and β parameter, are calculated as follows:

$$v_{n-1}(t + \tau) = v_{n-1}(t) - \alpha(t) = v_{n-1}(t) - (a_{n-1,min}(t) \times \tau + a_{jerk} \times \tau^2) \quad (9)$$

$$v_{n+1}(t+\tau) = v_{n+1}(t) - \beta(t) = v_{n-1}(t) - (a_{n-1,max}(t) \times \tau - a_{jerk} \times \tau^2) \quad (10)$$

Where $a_n(t)$ and $v_n(t)$ is the acceleration and velocity respectively of vehicle n at time t, τ is the simulation time and α_{jerk} is the maximum allowed jerk.

4.4. Manual vehicle gap acceptance logic

The default gap acceptance process used by the commercial microsimulator is retained in its native state for manual vehicle operation (PTV Group, 2016). Gap acceptance in Vissim is contingent on the speed of the vehicle that is conducting the lane change and the speed of the follower in the target lane. The minimum headway required for a lane change to occur can be specified by the user but has a default value of 0.5 m. The minimum headway though is subject to change based on the travel speed, to satisfy the speed-dependant safety distance (mentioned in Eq. (8)).

4.5. CAV and non-CAV lane changing logic

Once the appropriate acceleration is set using the method in Sections 4.1 and 4.2, and the gap has been deemed acceptable using the method in Sections 4.3 and 4.4, the lane change occurs. The microsimulator controls the mechanics of lane changing (PTV Group, 2016); the microsimulator is responsible for setting the wheel angles and conducting the lane change manoeuvre.

Also, the VCCP algorithm is not responsible for evaluating the need to change lanes for the CAVs and manual vehicles, the microsimulator also handles this. In the event where a lane change is required, the CAV will emit a signal notifying surrounding vehicles of its intention to change lanes. The surrounding vehicles will facilitate the lane change by producing an adequate gap in the platoon using the car following acceleration algorithm outlined in Section 4.1. The lane changing vehicle will then evaluate the gap at each time step and change lanes once the gap acceptance criteria in Section 4.3 are met.

5. Case study

The microsimulation environment is based on the Geelong area of Victoria, Australia. This location is chosen due to its hybridisation of both a highway environment and a residential urban endowment. The area also has extensive publicly available data to use readily for calibration of the base model. Outlined in this section are the features of the case study and the structure of the experimentation.

5.1. Microsimulation network

Calibration has been conducted to retain realism. However, a DDI is artificially incorporated into the environment. The reason for adding a DDI is because this element of the transport network is increasing in popularity, resulting in it changing from being a rare occurrence in transport networks to becoming accessible by regular motorists. Also, the DDI is safer than conventional intersections because it has fewer conflict points between interacting movements. So, if safety improvements can also be seen for an intersection arrangement that is already safer than conventional intersections, then this would further attest to the benefits of CAVs. Provided in Fig. 6 is the contextualised modelling environment.

The elements of the network are as follows:

- Signalised Intersection: Four signalised intersections are present in the environment. One exists as a conventional four-way intersection, one is in the form of a DDI, and the other two are present at the motorway onramp and offramp.
- Priority Junctions: Eleven priority junctions are present in the form of four roundabout and seven give-way junctions.
- DDI Intersection: A DDI has been artificially added to the environment in the top left of the study area. The DDI is a network element that is increasing in popularity and warrants investigation. Its geometric and signal configuration makes it a safer intersection arrangement than conventional intersections.
- Highway Environment: The study area contains the M1 Geelong Ring Road (Princess Freeway). This highway contains two lanes in each direction with onramps accessing the motorway through a third tapered lane.

5.2. Model calibration

Model calibration is the process of ensuring that modelled network behaviour aligns with observed network behaviour. The objective function for calibration is to minimise the Geoffrey E. Havers (GEH) statistic and is a function of the observed and modelled volumes. The objective function is expressed as;

$$\min\{GEH = f(M, C)\} \quad (11)$$

Where, M and C are the modelled and counted traffic volumes respectively. The GEH statistic is calculated using;

$$GEH = \frac{|M - C|}{(0.5 \times (M + C))^{0.5}} \quad (12)$$

The GEH statistic is a means of measuring the deviation between observed and modelled traffic volumes, with deviations being weighted by the absolute size of the measurement. This method ensures that smaller modelled volumes need to be closer to observed volumes, while larger volumes have a degree of tolerance.

Calibration has been conducted following the Roads and Maritime Services (RMS) modelling guidelines (Roads and Maritime Services, 2013), where the origin-destination matrix has been iteratively adjusted in response to the deviation calculated between the observed and modelled flows. Similar methods have been used in a range of other studies (Oketch and Carrick, 2005; Hollander and Liu, 2008; Rahman et al., 2019; Chu et al., 2003). The GEH statistic is calculated for each turning movement or link flow independently. The accuracy of the calibration process is determined by assessing the portion of turning movements in the model that have a GEH statistic of less than the threshold recommended in the RMS Modelling Guidelines. The guidelines recommend that 85% of volumes have a GEH statistic of less than 5, and 100% are less than 10. The GEH Statistic for all major links in the network is provided in Fig. 7, showing that these criteria have been met.

The GEH statistic for the network as a whole, presented in Table 1, is calculated using the aggregate observed and modelled volumes on all links. Regardless of the method used to calculate total network GEH, it is well below the value of 5 set by RMS.

Average annual daily traffic (AADT) data used to calibrate the model is available publicly through the VicRoads open data platform (VicRoads, 2017). This database provides extensive coverage for the majority of Victorian arterial and motorway roads. The AADT was converted to the peak-hour AM flow using the “Typical Hourly Traffic Volume” provided by the Victorian Government (Victoria State Government, 2018). The typical hourly volumes were used to calculate an AADT to peak-hour volume conversion factor of 0.091.

Fig. 7 also provides the observed volume and modelled volume for all major links in the network. This figure shows that the modelled volumes along all major links are sufficiently close to observed values,

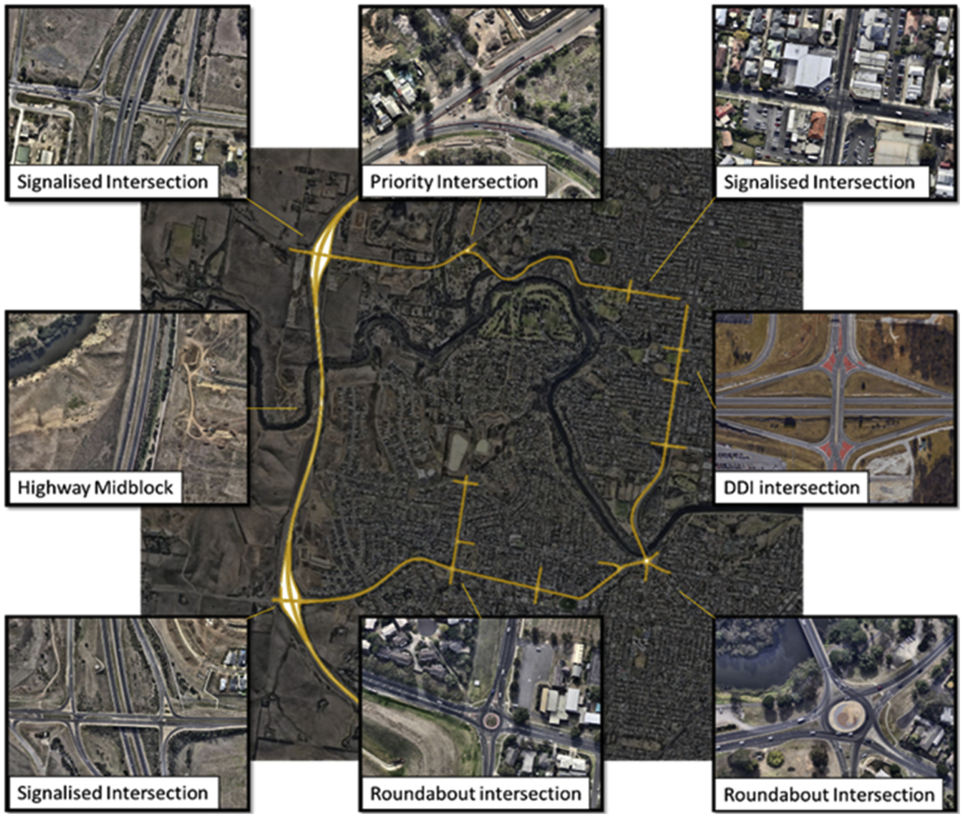


Fig. 6. The calibrated microsimulation network of the Geelong area in Victoria, Australia.

and the model is considered calibrated for the scope and purpose of this study. The calibrated demand was doubled during model runtime to ensure that latent demand would always be present in the model to not skew results.

The signal cycle times and phases have been designed to follow the RMS traffic signal design guidelines (Roads and Maritime Services, 2016). These guidelines are intended to incorporate a degree of optimality and safety in signal and phasing design. They aim to reduce the number of conflict points arising in a cycle and ban arrangements with more risk such as dual turns that filter through opposing traffic movements. This ensures that baseline results are not artificially accentuated through the implementation of un-optimised phasing.

Using travel time information along key links or queue length information at key intersections is a standard means of validating a microsimulation model. This study area is well under saturated and performs at near flee-flow speeds in the weekday peak period. The key routes in the microsimulation environment have an average travel speed that ranges between 94% and 107% of observed travel speeds, with observed travel speeds being obtained from Google Travel Time Data. A deviation of between -6% and 7% is considered acceptable for this microsimulation environment and is well within the 15% threshold identified by the RMS Modelling Guidelines.

The results in Sections 6 and 7 are discussed comparatively, in terms of relative increases and decreases. The use of the default SSAM parameters has been recommended by the United States Federal Highway Administration and several other studies. The SSAM parameters are discussed in greater detail in Section 5.3. Calibration through traffic volumes and validation through travel times on key routes indicates that the origin-destination matrix, the network software parameters and the vehicle behavioural parameters are adequately calibrated.

5.3. SSAM parameters

The TTC and PET values were set to 1.5 s and 5 s respectively for the manual vehicles, defaults recommended by the software to reflect human capabilities. The rear end angle and crossing angle were set to 30° and 80° respectively, also defaults recommended by the software. These values have been calibrated and recommended by the United States Federal Highway Administration (Gettman et al., 2008; Sabra et al., 2010) and have been used in a number of other studies (Stevanovic et al., 2013; Wu et al., 2018; Huang et al., 2013; Ni et al., 2013; Stamatiadis et al., 2013). The results are presented as a percentage difference between the base case and each scenario, meaning that biases inherent to the base case are also contained within each scenario tested.

The standstill and following distance for CAVs were reduced to one-third. For this reason, the TTC and PET values defining CAV conflicts have also been reduced to one-third.

5.4. Experimentation structure

Between the different scenarios, the CAV penetration rate is increased in 10% increments from 0% being the base case with a fully manual fleet to 100% being the fully autonomous case. Three random seeds are used in each of these scenarios. The location of the results reported in Section 6 are as follows:

- Signalised Intersection – Located on Hamilton Highway, at the north-east end of the study area.
- DDI North – Located on Shannon Avenue, the northern end of the DDI.
- DDI South – Located on Shannon Avenue, the southern end of the

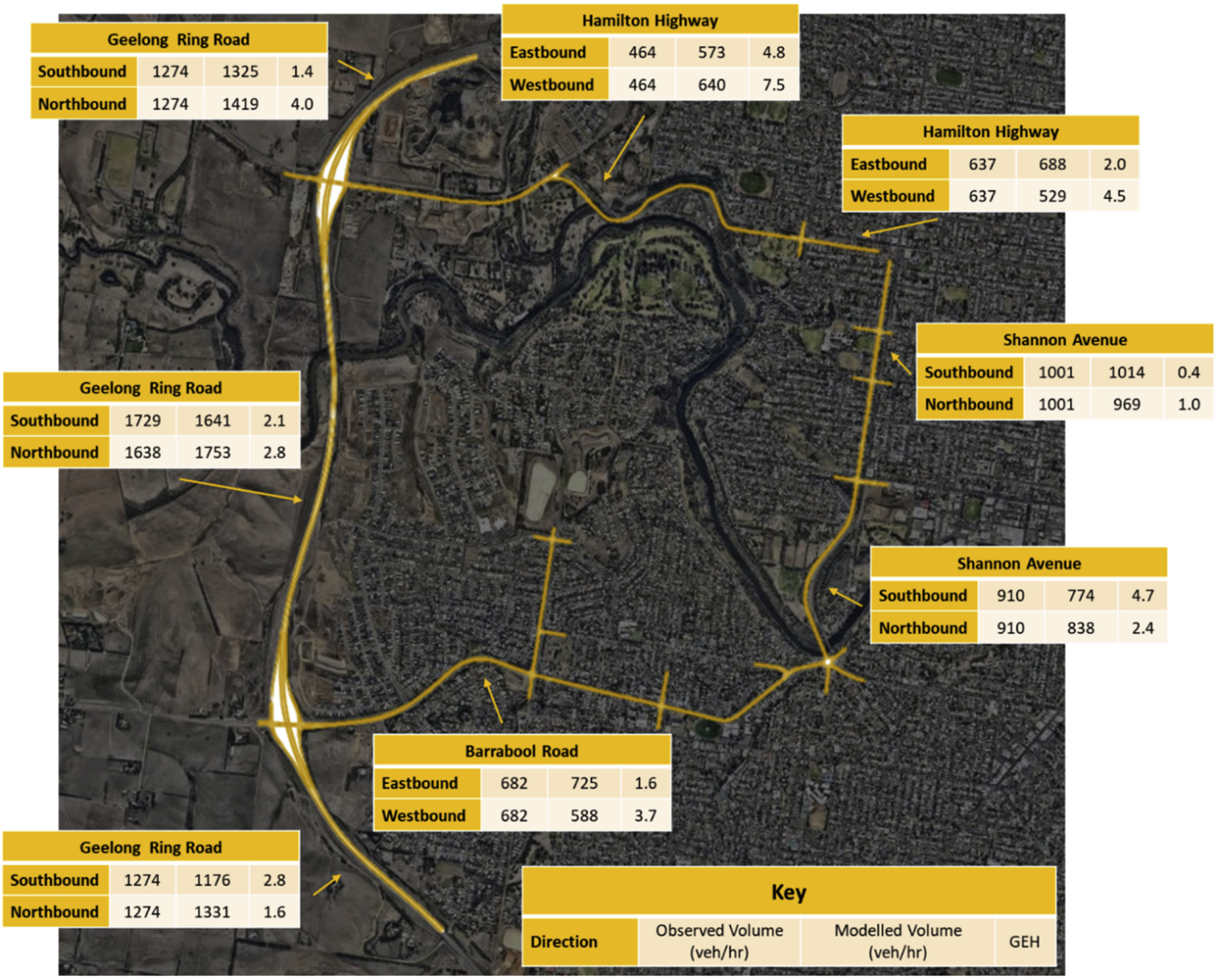


Fig. 7. GEH statistic for links in the network, showing that the model is calibrated and fit for purpose.

Table 1
Network scale calibration results using the GEH statistic method.

Method	GEH
Sum of total volumes on links	1.05
Weighted average of the GEH on individual links against the observed volume	2.65
Weighted average of the GEH on individual links against the measured volume	2.69

DDI.

- Roundabout – Located at the intersection of Barrabool Road and Shannon Avenue, at the south-east end of the study area.

6. Results

The results attained through microsimulation for the entire network are provided in Section 6.1. The results are then disaggregated by intersection type in Section 6.2. These results are the median of 3 random seeds. Using the median of multiple seeds accounts for the stochasticism of microsimulation modelling and the variability of day-to-day operation. The conflicts are further separated by the type of vehicle involved in the interaction. “M-M” represents a manual vehicle following and interacting with another manual vehicle, “A-M” represents a manual vehicle following a CAV, and “M-A” represents a CAV following a manual vehicle. Interactions involving a CAV following a CAV are excluded, as the assumption was made that CAVs are safe in their interaction with other CAVs and that SSAM flags their behaviour as overly aggressive and potential conflicts when compared to human driving.

6.1. Conflicts on highways

Fig. 8 shows that a 10% penetration of CAVs accompanies a 56% reduction in potential conflicts for the entire network. However, 84% of the 4341 conflicts observed in this modelling environment occurred in segment midblocks during lane changing and weaving actions. The remaining 16% of conflicts that occurred at intersections show results substantially less drastic than that observed for the entire network. The dramatic reduction in midblock conflicts is attributed to two factors. The first is that by increasing the proportion of CAVs in the network but holding the total demand constant, platooning operation increased the number of inter-platoon gaps in road segments. These gaps are then

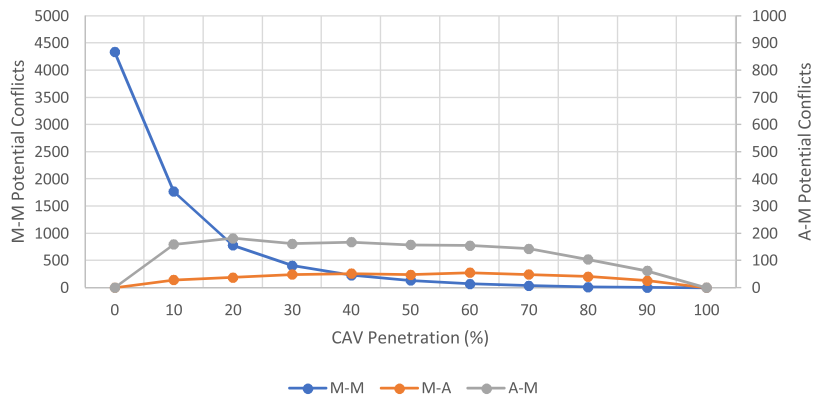


Fig. 8. Number of potential accidents within the environment, in 10% increments of CAV penetration.

Table 2
Tabular representation of the inter-platoonal headway distribution for the fleet along the highway.

CAV Penetration	Average Headway (sec)	Change in Average Headway	Headway Standard Deviation (sec)	Change in Headway Standard Deviation
0	5.326		2.888	
10	5.394	1.3%	2.980	3.2%
20	5.453	1.1%	2.978	−0.1%
30	5.420	−0.6%	2.991	0.4%
40	5.326	−1.7%	3.087	3.2%
50	5.453	2.4%	3.110	0.7%
60	5.562	2.0%	3.087	−0.7%
70	5.865	5.5%	3.180	3.0%
80	5.967	1.7%	3.246	2.1%
90	5.988	0.4%	3.213	−1.0%
100	6.266	4.6%	3.299	2.7%

The average headway on the highway increases by 2.4% (0.13 s) with the first 20% penetration of CAVs. This amounts to a distance headway increase of 3.18 m and 2.12 m on highways and suburban roads respectively. This headway increase is equivalent to approximately 106% the size of a small car or 71% the size of a medium car (Mechanic Base, 2019), which is substantial additional buffer room in lane changing, especially when the CAVs in this study are designed to be wholly altruistic and cooperative. Perhaps if a demand increase accompanied CAV penetration, average headways in the network would not increase as significantly, and conflict rates would stay consistent until higher penetrations of CAVs.

Fig. 9 provides a visual representation of the change in headway distribution. The headways are segregated in 2-second headway bins. What this figure shows, in complement to Table 2, is that not only does the mean headway drift towards larger values, but the occurrence of small (less than 2 s) and large (greater than 6 s) headways increases. The significance of this is once again that when demand is held constant, and CAV penetration is increased, this results in the formation of more platoons and increasing inter-platoon gaps, making lane changing safer for manual vehicles.

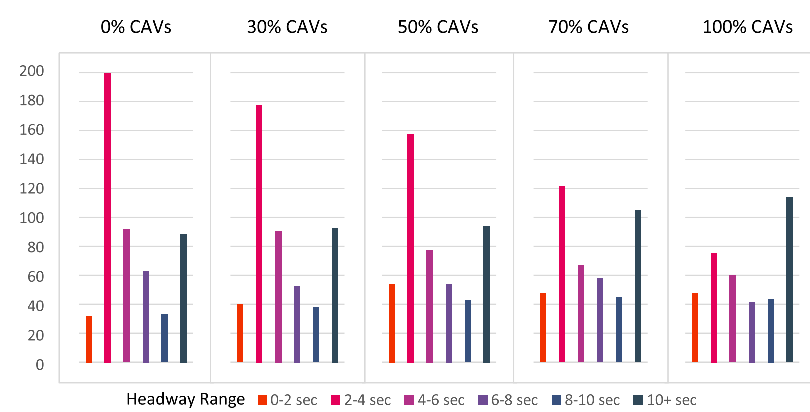


Fig. 9. Distribution of vehicle headways on the highway as the penetration of CAVS in the network increases.

leveraged by manual vehicles to conduct lane changes. The second cause is that by introducing CAVs into the fleet, the frequency of manual vehicle interactions is reduced, naturally adding to the reduction in manual vehicle conflicts.

The inter-platoon headway distribution of vehicles in 10% increments of CAVs has been calculated and provided in Table 2 using detectors throughout the highway. This table indicates that the average headway increases by 17.65% (0.94 s). On an average Australian highway at 90 km/hr or average suburban road at 60 km/hr, this amounts to a distance headway increase of 23.5 m and 15.7 m respectively, justifying the long-term reduction in conflicts with increasing CAV penetration.

6.2. Conflicts at intersections

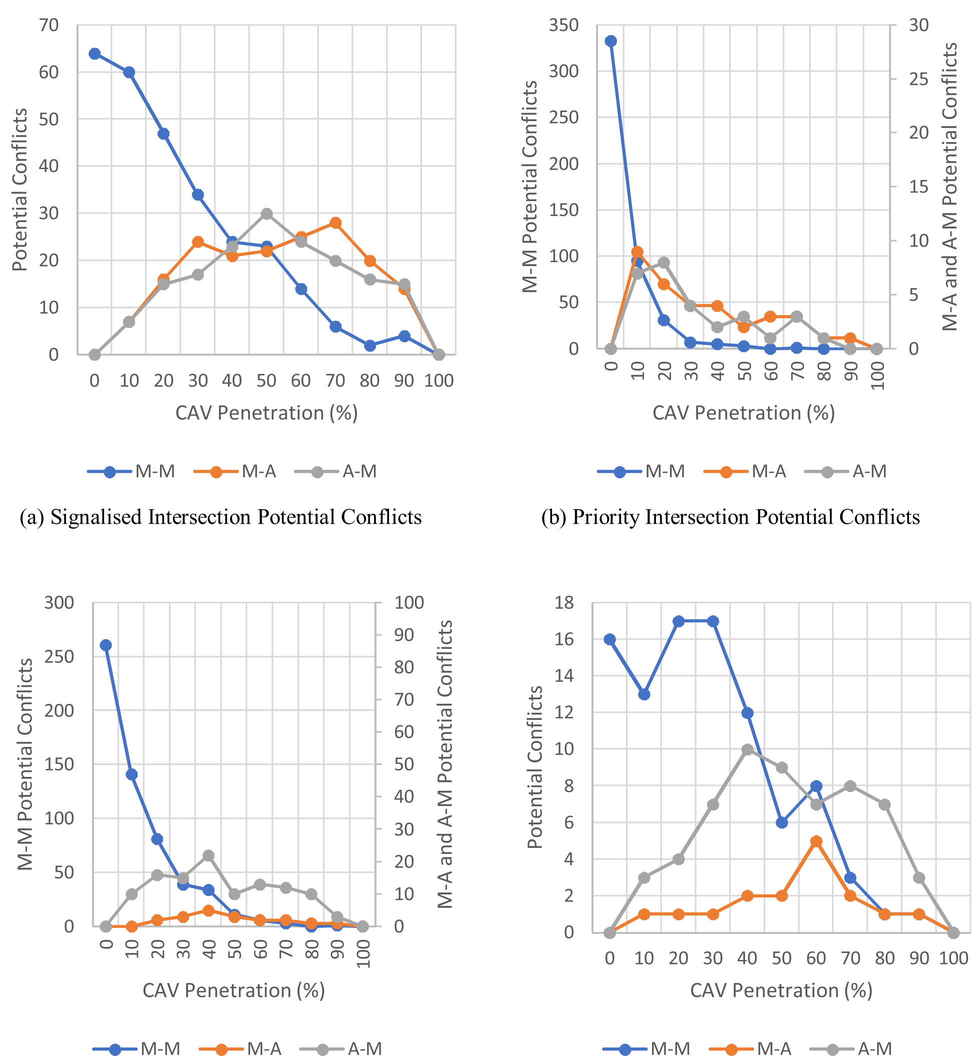
When rates of conflicts are observed at a granular intersection level, as shown in Fig. 10, the increase in safety is significantly less. On the contrary, the microsimulation modelling indicates that while conflicts between manual vehicles decline, the conflicts between CAVs and manual vehicles increases disproportionately, resulting in an initial increase in intersection conflicts at low CAV penetration before a decline in conflicts for higher CAV penetration. For the first 20% of CAV penetration, the signalised, priority, roundabout and DDI intersection show a change in conflicts of +22%, -87%, -62% and +33% respectively.

Signal controlled intersections such as the signalised intersection and DDI intersection both show an increase in total conflicts for low penetrations of CAVs, whereas the priority-controlled intersections such as the priority intersection and roundabout both show an immediate and significant reduction in conflicts. This observation provides further confirmation of the notion of vehicle behaviour in the “dilemma zone” being the cause of much of the safety concerns at signalised intersections. The aggressive and dangerous behaviour during amber signalling phases continues to drive conflict rates in signalised environments.

Also, Fig. 10(a) and (d) indicate that while manual following vehicles are responsible for the increase in conflicts at the DDI intersection; this is not the case with the signalised intersection, where CAV following vehicles drive the increase in conflicts. The differentiating factor between the two intersections is the geometry, where turning radii are significantly higher in the signalised intersection than the DDI intersection. This difference raises the question of whether geometry and turning radii continue to affect vehicle safety, as much of the literature’s crash prediction models suggests it does for manual vehicles; or if this occurred in the data as a result of a limitation in the software. The commercial microsimulator returns headway as the front-bumper-to-front-bumper distance between vehicles. During a turn, however, the cars are not lateral in the same plane, causing their headway to be passed to the VCCP algorithm as marginally higher than actual. The algorithm compensates by accelerating and reducing the gap. SSAM, however, uses both the front and rear bumpers position in the identification of conflicts, with the marginal decrease in the gap between vehicles being considered a potential conflict. This behaviour may result in SSAM identifying an artificial increase in conflicts for cases where CAVs are the following vehicle.

Between the 0% CAV base scenario and the 90% penetration scenario, microsimulation modelling indicates that signalised intersections experience a 48% reduction in conflicts, priority intersections experience a 100% reduction in conflicts, roundabouts experience a 98% reduction in conflicts and DDIs experience an 81% reduction in conflicts. The greater reduction in conflicts observed at the two priority intersections can be attributed to the same factors mentioned above to explain the reduction in segment midblocks. Also, the stringent gap acceptance and altruistic nature of vehicle cooperation reduce conflicts at lane changes such as that occurring at priority intersections.

Results for the DDI intersection presented in Fig. 10(d) shows an increase in conflicts when transitioning from 10% to 20% CAVs and 50% to 60% CAVs. This is attributed to two factors. The first is that the number of conflicts at this intersection is relatively small, at 16 in the base scenario. This means that minor fluctuations caused by the



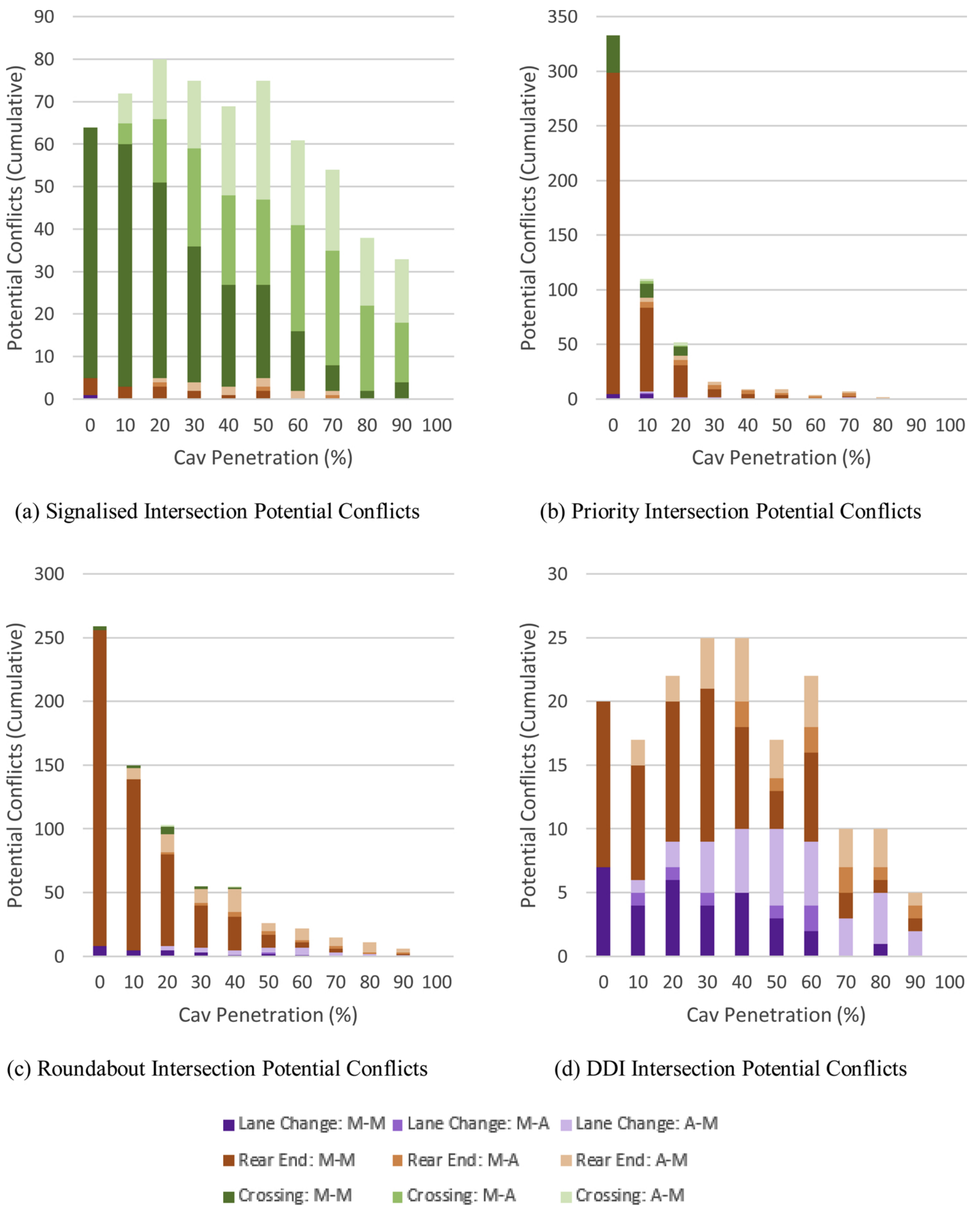
(a) Signalised Intersection Potential Conflicts

(b) Priority Intersection Potential Conflicts

(c) Roundabout Intersection Potential Conflicts

(d) DDI Intersection Potential Conflicts

Fig. 10. Number of potential accidents during different situations in the microsimulation environment, in 10% increments of CAV penetration.



(a) Signalised Intersection Potential Conflicts

(b) Priority Intersection Potential Conflicts

(c) Roundabout Intersection Potential Conflicts

(d) DDI Intersection Potential Conflicts

Fig. 11. Number of potential conflicts further segregated by conflict type.

variance between random seeds can potentially cause variances. The second reason is that this behaviour occurs in the lower penetration of CAVs scenarios where the likelihood of manual drivers interacting with one-another is still high as CAVs have not dominated the fleet.

These results are further segregated into conflicts-by-type as either a rear-end conflict, lane-change conflict or crossing conflict, and presented in Fig. 11. When the conflicts are segregated by type, the two signal-controlled intersections once again show distinct results from the two priority-controlled intersections. The priority intersection (Fig. 11(b)) and roundabout intersection (Fig. 11(c)) are dominated by rear-end collisions, with lane-changing and crossing conflicts being substantially lower. This outcome is consistent with the intentions of the VCCP algorithm outlined in Section 4. The CAV cooperative gap acceptance protocol forces the vehicle to communicate and facilitate the formation of appropriate gaps, while also having a strict acceptance criterion for gaps. This leads to a low level of lane changing conflicts shown in these figures. Network geometry explains the low level of crossing conflicts. A crossing conflict is defined occurring between 80° and 180° relative to the vehicle (refer to Fig. 2). However, due to the concentric direction of motion around a roundabout, such an angle is rare and difficult to achieve. This also applies to the priority intersection, where vehicles are travelling near parallel to the lane they are turning.

The signalised intersection and DDI however, show a significantly higher proportion of crossing and lane changing conflicts respectively. In the low penetration scenarios, CAV behaviour introduces more conflicts than the manual vehicle conflicts that it mitigates (Fig. 11(a)). This figure also indicates that the CAV as the following vehicle contributes a larger share of the newly occurring conflicts. The CAV gap acceptance criteria are based on a headway and speed threshold, meaning that the CAVs do not behave differently depending on the following vehicle type. Allowing them to accept small gaps even with manual vehicles is resulting in one of two outcomes. Either the aggressive 0.5 m headway is not appropriate for a heterogeneous mixed fleet environment, or the two vehicles being in different planes of motion is resulting in a mismatch between the headway calculated by Vissim and the headway calculated by SSAM. Both have been discussed prior in Section 6 when commenting on the results of Fig. 10.

The lane-changing conflicts increase by up to 5 conflicts at the DDI intersection (Fig. 11(d)). It is difficult to comment on the statistical

Table 3
Standard deviation for the number of conflicts for different intersections in the environment.

Intersection Type	Interaction Type	Penetration										
		0	10	20	30	40	50	60	70	80	90	100
Complete Network	M-M	225	50	46	11	4	8	16	8	1	1	0
	A-M	0	10	4	11	12	12	9	7	3	3	0
	M-A	0	0	7	8	5	3	6	4	7	5	0
Signalised Intersection	M-M	3	6	7	3	5	0	1	3	2	1	0
	A-M	0	2	3	2	5	6	6	2	1	2	0
	M-A	0	2	4	2	4	5	5	5	4	3	0
Priority Intersection	M-M	41	34	20	9	6	0	2	1	0	0	0
	A-M	0	5	8	1	2	2	1	1	2	1	0
	M-A	0	2	0	2	1	0	2	2	1	0	0
Roundabout Intersection	M-M	5	30	6	9	6	1	2	0	1	1	0
	M-M	0	0	1	0	1	0	1	1	1	0	0
	A-M	0	0	1	2	3	1	2	2	2	1	0
DDI Intersection	M-M	4	1	2	4	1	2	2	1	1	0	0
	A-M	0	0	1	2	3	1	2	2	2	1	0
	M-A	0	1	1	0	2	1	2	2	1	0	0

Table 4
Number of conflicts for different intersections in the environment for the "M-M" interaction type, normalised for the volume of manual vehicles remaining in the network.

Intersection	CAV Penetration (%)										
	0	10	20	30	40	50	60	70	80	90	100
Complete Network	4341	1966	976	580	388	270	180	133	75	70	0
Signalised Intersection	64	67	59	49	40	46	35	20	10	40	0
Priority Intersection	333	106	39	10	8	6	0	3	0	0	0
Roundabout Intersection	261	157	101	56	57	22	15	10	0	10	0
DDI Intersection	16	14	21	24	20	12	20	10	5	10	0

significance of this outcome, considering that it may be the result of deviations between random seeds and the inherent stochasticity of microsimulation modelling. This outcome warrants further investigation.

Table 3 provides the standard deviation for the results attained from the different random seeds. The standard deviation between seeds provides insight into the uncertainty and variability that is introduced to the network through CAVs. Relative to the observed values, the low standard deviations indicate that CAV presence does not cause uncertain and erratic or dangerous behaviour in manual vehicles during mixed fleet scenarios.

Table 4 provides the results for only the "M-M" interaction type, normalised to represent the number of conflicts between manual vehicles when factoring in the decreasing number of manual vehicles in the microsimulation environment. The decreasing trend in this table at comparable rates to that presented in Figs. 8 and 10 indicates that the results have not been skewed by a decreasing presence of manual vehicles in the network.

The modelling indicates that even if a driver continues to operate a manual vehicle in an environment with CAVs, the likelihood of the manual driver being involved in an accident with another manual or autonomous vehicle decreases.

7. Discussion

A clear pattern emerges when observing the number of potential conflicts for the entire network. As the penetration of CAVs increases, the number of accidents involving manual vehicles decreases. This result is attributed to several factors. Firstly, the CAVs are designed to treat an amber light as a red light, eliminating the "dilemma zone" that has been established as the cause of much of the conflict at signalised intersections (Papaioannou, 2007). Additionally, CAV behaviour has been designed to be cooperative and altruistic. The gap acceptance criteria ensure that vehicles do not merge or change lanes into a gap that results in unsafe headways, nor do the vehicles merge if this action results in excessive braking for the merging or following vehicle. Managing imprudent lane changes with CAVs through cooperation limits variations in speed and reduces conflicts, which was a major source of conflicts in this environment. The effect would be expected to be higher in cases where the following vehicle is distracted as this leads to an eight-fold increase in the likelihood of collisions (Carbaugh et al., 1998). Finally, the CAVs have access to complete and correct information regarding their surroundings, with vehicle reaction time restricted to the minimum simulation time step of the microsimulator. This information means that CAVs do not make assumptions regarding the spatial and behavioural characteristics of surrounding vehicles. Having access to this precise information means that minimum safe headway requirements are never violated, further reducing the likelihood of potential conflicts.

The results indicate that CAVs in the short term have the potential to increase conflicts at intersections, findings that are consistent with the Tibljaš et al. (2018) and Turner and Roozenburg (2006). The 0.5 m headway appears to be inappropriate in a mixed fleet setting with substantial heterogeneous behaviour. Once homogeny returns to the vehicle fleet in higher CAV penetrations, the use of this headway results in a decrease in conflicts. However, it should be noted that demand was kept constant throughout the study, meaning that an increase in CAVs leads to an increase in gaps in the network. This may be the cause of the reduction in conflicts, warranting a further investigation.

In highway environments, the results of this study show benefit to safety from a 10% CAV penetration rate. Other studies do not show significant improvements until a CAV penetration of 20% to 30% (Rahman et al., 2019; Papadoulis et al., 2019). The limitations of the other studies are in their emulation of CAV behaviour. These studies have opted to use rudimentary autonomous features such as adaptive cruise control and lane guidance to emulate what is a highly promising technology that is currently in its infancy. These studies have incremented CAV penetration in 10% increments to 100%. To “implement lower level automation features under connected vehicle environment which is available in many vehicles in the market” (Rahman et al., 2019) has significant caveats as CAV technology that will not be ready, implemented or see significant market penetration for decades to come. Computational capabilities and data processing techniques improve at an exponential rate. The approach used in this study in applying highly refined CAV operations such as precise vehicle co-ordination, minimal headways and complete co-operation may be optimistic. While a 10% CAV penetration is many years away, CAV operation may not match the assumptions made in this study, but it provides new insights when it comes to the definition and refinement of the assumptions of CAV behaviour for future studies.

The results also show that when CAV penetration increases and homogeneous operation returns to the network, potential conflicts are likely to decrease, consistent with much of the literature. The initial 10% penetration of CAVs results in an approximate 56% network-wide reduction in conflicts, with 8% of accidents at this penetration involving a CAV. An accurate cost of a CAV is difficult to identify but is estimated to start at $250,000 (USD) (LeVine, 2017). While this cost remains at approximately ten times higher than the cost of an average car, a 56% reduction in network-wide conflicts and 8% of conflicts involving a CAV still leads to an estimated economic saving of 22% when considering only vehicle replacement costs. As CAV become cheaper, this economic benefit will become higher. However, using the higher purchase price, this amounts to a saving of approximately AUD $786 million annually for Australia alone. This figure is calculated based on the AUD$2.8 billion cost to the economy found in the BITRE study (Bureau of Infrastructure, Transport and Regional Economics, 2006), adjusted for inflation at 1.9% per annum using the consumer price index (Australian Bureau of Statistics, 2018). This figure is conservative and does not include the potential savings that arise from costs involved in damage to property and infrastructure. This figure also does not consider the effects of reducing CAV prices, which would further increase economic savings.

This figure also does not consider the savings in infrastructure development. Most transport infrastructure contains redundancies that are designed to facilitate the movement of emergency vehicles or operate if an accident occurs. This emergency infrastructure consists of emergency-vehicle-only lanes on motorways or shoulders on arterials. These savings in construction will be significant for a country such as Australia, where development in metropolitan areas has occurred near existing transport corridors, without residual space to grow. All future projects in the Sydney and Melbourne long-term master plans contain vastly more expensive tunnelling components where the cost of tunnelling increases exponentially with the number of lanes and tunnel diameter.

The DDI (Fig. 10(d)), which is designed to be safer than conventional intersections, experiences a more gradual improvement in safety. Reductions in the occurrence of conflicts do not begin until CAV penetration reaches 30%, indicating that the inherent safety of DDIs and lack of conflict points requires a higher penetration of CAVs to extract similar benefits to that which can be extracted at lower penetration rates from traditional intersections. The signalised environment (Fig. 10(a)) showed the highest increase in the number of conflicts of the four scenarios for the initial 10% penetration of CAVs. This has been addressed as being the results of more dangerous driving by manual drivers in the “dilemma zone”, potentially decreasing safety for CAVs at low headways.

When observing the standard deviations between seeds, a notable observation is that the standard deviation is higher for lower penetration rates of CAVs. This indicates that the presence of CAVs in a mixed fleet environment disrupts the degree of homogeneity that is present in both a completely manual and heavily autonomous environment. While human behaviour and personal preferences regarding speed, headway and other driving elements cause variances in a traffic stream, agents do not generally deviate substantially from accepted bounds. Speed is regulated by design limits and headway is governed by risk aversion. CAVs also exhibit homogeneity, as they follow speed and headway requirements dictated by algorithms. However, whilst the CAVs in this study adhere to a 0.5 m headway, the manual vehicles standstill at a distance four times higher than this, and drive with a headway significantly higher. The difference in the fundamental behaviour of these vehicle types disrupts the order and uniformity of the fleet. This leads to a high degree of variability between the seeds regarding the prevalence and structure of gaps in conflicting traffic streams, which in turn increases the variability in the number of potential conflicts in the network. This behaviour, however, decreases as CAV penetration increases and uniformity in behaviour once again returns to the network.

Though the implementation of CAVs leads to the idealised vision of a zero-accident environment, in the interim smart infrastructure and design decisions will still need to be made to maintain safety. Crash prediction models are useful in assessing the safety of designs and will, therefore, need to be recalibrated to incorporate the presence and conflict characteristics of CAVs.

A reduction in the likelihood of accidents as observed here means that the way vehicular insurance is structured may also require reform. As society embraces the sharing economy with CAVs servicing travel requirements on-demand, and their tendency to be safer as shown in this study, insurance agencies may benefit from a restructure in the way that insurance is sold. Policies involving insuring the driver as opposed to insuring the vehicle may warrant investigation.

8. Conclusion

In this study, the authors investigated the effect of CAV penetration on the safety on the road network. This investigation was conducted using microsimulation modelling, with CAV behaviour being emulated using a custom-developed external control algorithm and the likelihood of potential conflicts was identified using the surrogate safety assessment module. The contribution of this work lies in its development of this custom control algorithm for CAV emulation and assessment of CAV safety based on microsimulation testing. The results indicate that while CAV operation seems to show a significant overall improvement in safety, this improvement is concentrated at segment midblocks. The signalised intersections show an increase in potential collisions for low penetration rates, while the priority intersections show an immediate and significant decrease. As CAV penetration increases, the potential conflicts in all settings declines. Reductions in potential conflicts are greater in priority-controlled intersections such as roundabouts and give-way environments, as compared to signalised intersections.

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