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Investigating safety impacts of autonomous vehicles using traffic micro-simulation

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Abstract

Autonomous Vehicle (AV) technology has advanced rapidly in recent years with some automated features already available in vehicles on the market. AVs are highly expected to reduce traffic crashes as the majority of crashes are related to driver errors, fatigue, alcohol, or drugs etc. However, very little research has been conducted to estimate safety impacts of AVs. This paper aims to investigate the safety impacts of AVs using a simulation-based surrogate safety measure approach. To this end, safety impacts are explored through the number of conflicts extracted from VISSIM traffic micro-simulator using Surrogate Safety Assessment Model (SSAM). Behaviours of Human-driven Vehicles (HVs) and AVs (level 4 automation) are modelled within VISSIM's car following model. The safety investigation is conducted for two case studies, including a signalised intersection and a roundabout, under various AV penetration rates. Results suggest that AVs improve safety significantly with high penetration rates, even when they are expected to travel with shorter headways to improve road capacity. For the signalised intersection, AVs reduce the number of conflicts by 20% to 47% with the penetration rates of between 50% and 100% (statistically significant at $p<0.05$). For the roundabout, the number of conflicts is reduced by 29% to 32% with the 100% AV penetration rate (statistically significant at $p<0.05$).[1]

Keywords: autonomous vehicles, driverless vehicles, safety, crash, conflict, simulation

1 Introduction

Autonomous Vehicle (AV) technology has advanced significantly in recent years. In Australia, AV testing has been first introduced in South Australia's roadways in 2016 (DPTI, 2016). AVs have the potential to significantly improve road safety as the majority of crashes are related to driver errors, fatigue, alcohol, or drugs (NHTSA, 2008; BITRE, 2011). It is also expected that AVs can travel with shorter headways due to improved safety, leading to increased road and intersection capacities (Hoogendoorn et al., 2014). AVs would also provide improved mobility to the disabled, those who are too young to drive, and older people (Truong et al., 2017). Other potential benefits of AVs include enhanced productive use of travel time, fewer emissions, better fuel efficiency, and reduced parking costs.

Several studies have attempted to examine safety benefits of AVs using different approaches. Fagnant and Kockelman (2015) assumed near-elimination of human errors, which is related to main factors of over 90% of crashes in the US, from AV technology. Rau et al. (2015) developed a method to identify crashes, which could be addressed by AV technology, by mapping automated vehicle functions to five layers of crash information (location, pre-crash scenario, driving conditions, travel speed, and driver condition). Using data from AV testing, Schoettle and Sivak (2015) found that AVs were not at-fault in any crashes and the overall injury severity was lower for crashes involving AVs than for crashes involving Human-driven Vehicles (HVs). Using traffic micro-simulation, Kockelman et al. (2016) found that in general

[1] This is an abridged version of the paper originally submitted for ATRF 2017. For further information about this research please contact the authors.

AVs reduce the number of potential conflicts based on surrogate safety measures and thus improve safety. In their study, a car-flowing model based on the Wiedemann 74 and 99 models was adopted for HVs. This model was then modified to model behaviours of AVs. For example, as AV behaviours are expected to be less stochastic, the variance of the driver random terms was set to zero. Other parameters, such as minimum acceptable gap for merging or turning, sight distance, and lane change preferences, were modified to make the AV behaviours more conservative as automakers would be very unlikely to make AVs aggressive due to their potential liability. In other words, AVs were modelled to be more cautious than human drivers and therefore had fewer potential conflicts. However, there is another possible scenario, particularly in the long run, where AV behaviours could be less conservative due to shorter headways and more aggressive acceleration as AVs are anticipated to increase road and intersection capacities. Thus, it is also important to investigate the safety impacts of AVs with such behaviours.

This paper aims to investigate safety impacts of AVs using a simulation-based surrogate safety measure approach. AVs are modelled with anticipated behaviours, such as shorter headways. Safety performance of AVs is considered with varying penetration rates in two case studies, including a signalised intersection and a roundabout.

2 Methodology

To understand the safety implications of AVs, VISSIM (PTV, 2016) was used as the traffic micro-simulation platform while Surrogate Safety Assessment Model - SSAM (Gettman et al., 2008) was used to extract the number of potential conflicts based on a surrogate safety measure from simulated data.

2.1 Simulation platform

Behaviours of Human-driven Vehicles (HVs) were modelled using VISSIM's Wiedemann 99 car following model with default parameters. This provides a reasonable base model for human drivers. This paper assumes that AVs are fully automated with level 4 automation (NHTSA, 2013). Previous studies have shown that parameters of the VISSIM car following model can be modified to model behaviours of AVs (Bierstedt et al., 2014; Atkins, 2016). Two sets of AV parameters adopted from Atkins (2016) and PTV (2017) were considered in this study. Table 1 presents a set of HV parameters and two sets of AV parameters.

Table 1: Parameters for HV and AV behaviours

Parameter	Description	HV	AV-1	AV-2
CC0 Standstill distance (m)	The desired distance between stopped vehicles	1.5	0.5	0.75
CC1 Headway time (s)	The gap in seconds that a vehicle keeps	0.9	0.5	0.45
CC2 Following variation (m)	The distance in addition to the allowed safety distance that is permissible before the vehicle-drive unit moves closer to the proceeding vehicle.	4	0	2
CC4 Negative following threshold	Control speed differences during car following	-0.35	0	-0.1
CC5 Positive following threshold	Control speed differences during car following	0.35	0	0.1
CC6 Speed dependency of oscillation	Influence of distance on speed oscillation (the variation of speed around the desired speed)	11.44	0	0
CC7 (m/s^2)	Influence of vehicle acceleration during car following oscillation	0.25	0.45	0.25
CC8 (m/s^2)	Desired acceleration when starting from standstill	3.5	3.9	3.5
Look ahead distance	Number of observed vehicles the model will look ahead at	2	10	2

Note: AV-1 is adopted from Atkins (2016); AV-2 is adopted from PTV (2017)

Parameters for AVs reflect more assertive behaviours, such as shorter standstill distance (CC0) and shorter safety distance (lower headway CC1 and following variation CC2). Smaller values of the negative following threshold (CC4) and positive following threshold (CC5) reflects a more sensitive reaction of AVs to the acceleration or deceleration of the preceding vehicle. As AVs can strictly follow the desired speed without oscillation, CC6 is set as zero. According to Atkins (2016), AVs can also have more aggressive acceleration (higher CC7 and CC8) and a higher number of observed vehicles due to connected vehicle technology. Although the exact behaviours of AVs are largely unknown at this stage, the modification of these parameters should be able to reflect the anticipated AV behaviours.

2.2 Surrogate Safety Measures

It is generally considered that a TTC, equal or less than 1.5 seconds, would result in an unsafe situation (Gettman et al., 2008; Truong et al., 2015). This threshold of 1.5 seconds is therefore applied for potential conflicts involving HVs (HV-HV and HV-AV). However, for potential conflicts between AVs, the TTC threshold will be set as 1 second. The reasoning behind the lower TTC threshold for AVs is due to their ability to react to situations a lot faster that their human counterparts, particularly with connected vehicle technology. Post Encroachment Time (PET), defined as the time difference between when the leading vehicle occupied a location and the trailing vehicle arrived at this location, is usually used to identify conflicts in combination with TTC. A PET threshold of 5 seconds is used as the default value in SSAM (Gettman et al., 2008).

2.3 Case studies

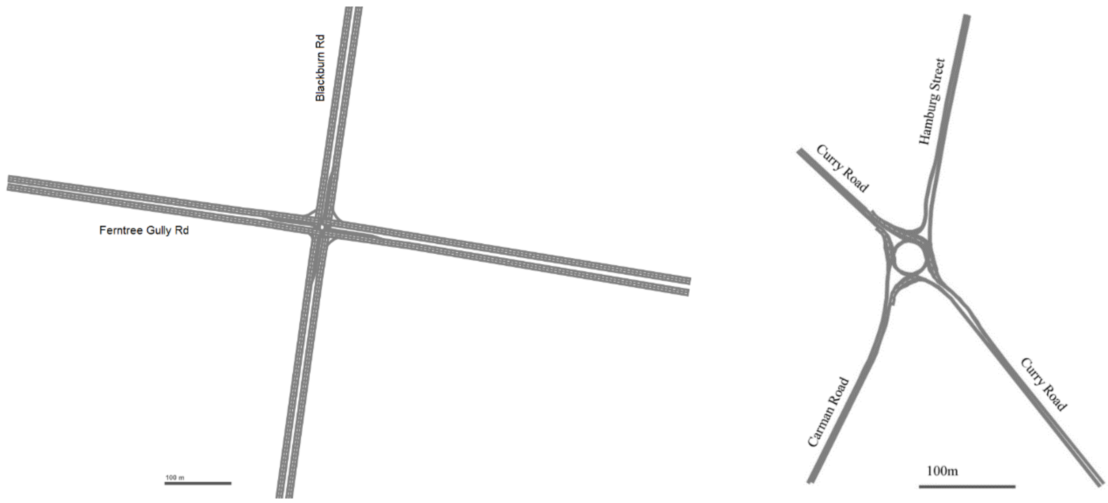
Using the aforementioned approach, safety impacts of autonomous vehicles were investigated in two case studies, including a signalised intersection and a roundabout (Figure 1). Details of each case study are presented in the following sub-sections.

2.3.1 Signalised Intersection

The intersection of Ferntree Gully Road and Blackburn Road in Melbourne, Australia was chosen as the first case study. Both roads are 3-laned arterial roads with several bus routes. The intersection also has a right turning lane on all four approaches and a left turning slip lane on three approaches. Traffic volumes per intersection approach range from 760 to 2260veh/h. The traffic composition was 95% cars and 5% trucks. The bus routes with far-side and mid-block bus stops were also modelled with scheduled arrival times.

Figure 1: Case studies

a) Signalised intersection | b) Roundabout



The variance in desired speed distributions is another key element that varies from HVs and AVs within the network. It can be assumed that the variation in the desired speed distribution of a human driver would be much larger than that of an AV due to the nature of AVs having much more precise throttle control. Based on field conditions, the desired speed distribution for HVs ranges between 65km/h and 75km/h. AVs' desired speed distribution has the same mean, but a narrower range between 69km/h and 71km/h.

2.3.2 Roundabout

The second case study was based on a roundabout model that was provided with SSAM. This is a four-legged roundabout in Schenectady, New York. Traffic volumes per lane on each approach range from about 490 to 1050veh/h. Traffic composition was 96% cars and 4% trucks. The desired speed distribution for HVs ranges between 48km/h and 58km/h. Like the first case study, AVs' desired speed distribution has a narrower range between 52km/h and 54km/h.

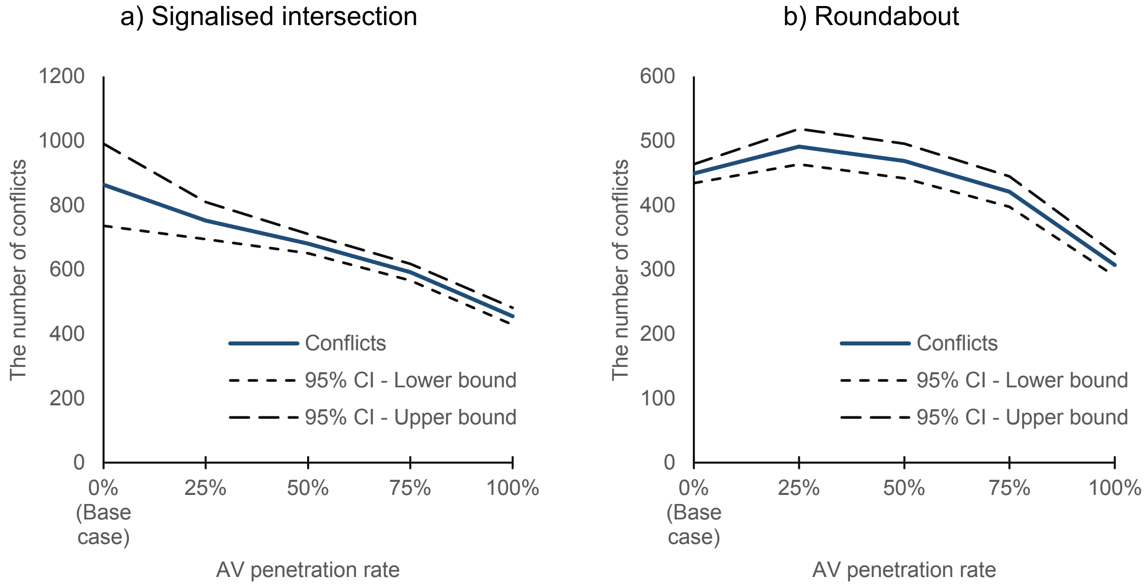
2.3.3 Scenarios

Varying penetration rates of AVs, including 0% (base case with 100% HVs), 25%, 50%, 75%, and 100%, were analysed for each case study. For each scenario, the simulation time was set to 1 hour, excluding a warm-up time of 10 mins. All scenarios were modelled with 10 simulation time steps per second to better accommodate AVs' shorter headways. Due to stochastic nature of micro-simulation, 20 runs with different seed numbers were performed for each scenario to obtain reliable outputs (Truong et al., 2016).

3 Results and discussion

Results with the AV-2 parameters are presented in Figure 2. For the roundabout, the number of conflicts increases between the base case and 25% AV penetration rate, but decreases steadily between 25% and 75% AV penetration rates. Particularly with the 100% AV penetration rate, the number of conflicts is significantly lower at $p<0.05$ with an improvement of 32% compared to the base case. For the signalised intersection, the number of conflicts decreases as the AV penetration rate increases. Compared to the base case, the number of conflicts with the penetration rate of 50% or more is significantly lower at $p<0.05$, with improvements ranging from 21% to 47%. Particularly the number of conflicts with the 100% penetration rate is significantly lower compared to all other penetration rates.

Figure 2 Total number of conflicts by AV penetration rate (AV-2 parameters)



In general, there are similar patterns in safety benefits of AVs between the two set of AV parameters. However, the benefits obtained from AV-2 parameters are higher compared to those from AV-1 parameters (maximum benefit of 32% vs 29% for the roundabout, and 47%

vs 24% for the signalised intersection). It is noted that the AV-2 parameter set has higher standstill and following variation distances whereas the AV-1 parameter set has slightly higher headway, but more aggressive acceleration. Nevertheless, both AV parameter sets suggest safety benefits of AVs with high penetration rates.

4 Conclusions

This paper has investigated safety impacts of Autonomous Vehicles (AVs) using traffic micro-simulation and Surrogate Safety Assessment Model (SSAM). Safety performance of AVs (level 4 automation – fully automated) in signalised intersection and roundabout case studies was explored through the number of potential conflicts based on Time To Collision (TTC) and Post Encroachment Time (PET). VISSIM was adopted as the traffic micro-simulation platform to model behaviours of Human-driven Vehicles (HVs) and AVs. More assertive behaviours of AVs, such as shorter headways and more aggressive acceleration, were explicitly considered. Results suggest that AVs improve safety significantly with high penetration rates, even when they are expected to travel with shorter headways to improve road capacity. For the signalised intersection, AVs reduce the number of conflicts by 20% to 47% with the penetration rates between 50% and 100% (statistically significant at $p<0.05$). For the roundabout, reductions of between 29% and 32%, in terms of conflicts, are evident with the 100% AV penetration rate (statistically significant at $p<0.05$). An implication of these findings is that a high AV penetration rate might be required to deliver AVs' anticipated safety benefits.

The simulation-based approach presented in this paper provides an important tool to evaluate safety impacts of AVs, particularly when there has been very limited empirical data on safety performance of AVs. Nevertheless, there are limitations in the proposed approach, which should be addressed in future research. First, the ability to replicate how AVs will act within a real-world road network is limited due to the fact that AV technology is still being developed. It is therefore difficult to accurately represent how AVs will act in varying situations within a road network as their true behaviours are largely unknown. Although this study modelled AV behaviours by modifying VISSIM's car following model in accordance with recent literature, there is a clear scope to develop a more realistic model for connected AVs. Future research should also explore the impacts of vehicle-to-vehicle (V2V) safety technology and communication protocols (Harding et al., 2014). Next, potential conflicts in this analysis were solely based on TTC and PET. The use of other surrogate safety measures, such as deceleration rate required to avoid a crash (DRAC), and crash potential index (CPI), should be considered to increase the validity of the approach. It is also necessary to develop new surrogate safety measures for AVs due to their different behaviours. Finally, the study only considered two case studies, a signalised intersection and a roundabout. Therefore, to make reliable conclusions about the overall safety impacts of AVs on a large road network, more testings with various network settings under wide-ranging traffic conditions and AV penetration rates might be required.

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