Journal of Intelligent and Connected Vehicles
2023, **6**(4): 202–210
https://doi.org/10.26599/JICV.2023.9210007

Research Article

Micro-simulation insights into the safety and operational benefits of autonomous vehicles

Nalin Kumar Sekar[1], Vinayak Malaghan[2], Digvijay S. Pawar[3,✉]

[1]*School of Mechanical Engineering, Vellore Institute of Technology, Vellore 632014, India*
[2]*Department of Civil, Structural, and Environmental Engineering, Trinity College Dublin, The University of Dublin, Dublin 2, Ireland*
[3]*Department of Civil Engineering, Indian Institute of Technology Hyderabad, Kandi 502285, India*

Received: February 14, 2023; Revised: April 12, 2023; Accepted: May 6, 2023

ABSTRACT: Several past studies showed that Autonomous Vehicles (AVs) can reduce crash risk, stop-and-go traffic, and travel time. To analyze the safety benefits of AVs, most of the researchers proposed algorithms and simulation-based techniques. However, these studies have not assessed the safety benefits of AVs for different vehicle types under heterogeneous conditions. With this opportunity, this study focuses on the benefits of AVs in terms of safety for different penetration rates under heterogeneous conditions. This study considered three driving logics during peak hour conditions to assess the performance of AVs in terms of safety. In VISSIM, default driving behavior models for AVs were adopted to consider cautious and all-knowing driving logic and the third driving logic (Atkins) was modeled in VISSIM using parameters adopted from the previous studies. To this end, using VISSIM, the travel time output results were obtained. Also, using Surrogate Safety Assessment Model (SSAM), conflicts were extracted from output trajectory files (VISSIM). The results suggest that "cautious driving logic" reduced travel time and crash risk significantly when compared to the other two driving logics during peak hour conditions. Furthermore, the statistical analysis clearly demonstrated that "cautious driving logic" differs significantly from the other two driving logics. When Market Penetration Rates (MPR) were 50% or greater, the "cautious driving logic" significantly outperforms the other two driving logics. The results highlight that adopting "cautious driving logic" at an expressway may significantly increase safety at higher AV penetration rates (above 50%).

KEYWORDS: automated vehicles, driving behavior, penetration rates, driving logics and safety impacts

1 Introduction

Road traffic accidents are one of the leading causes of worldwide human fatality. The annual fatalities from road traffic crashes reached about 1.35 billion worldwide (World Health Organization (WHO, 2018)). As per WHO report, at least one of ten global crashes belongs to India (Ministry of Road Transport and Highways (MORTH, 2020)). Road crashes occur due to the interplay of three primary factors: road infrastructure, vehicle, and human factors (MORTH, 2020; Malaghan and Pawar, 2022). Of these, the factors related to human error are responsible for 4.9 million road crashes in India (MORTH, 2020). Rear-end, lane change, and crossing conflicts are significant crashes that occur due to human error (MORTH, 2020). Rear-end collisions contribute the highest percent (~40%) of crashes among the aforementioned crashes.

Autonomous Vehicles (AVs) can potentially reduce road crashes and travel time (Singh, 2015; Yue et al., 2018). AVs are expected to maintain smaller headway, resulting in increased capacity and travel time compared to human-driven vehicles (Hoogendoorn et al., 2014). With proper vehicle-to-vehicle (V2V) connectivity, each AV receives information (i.e., speed, deceleration, and acceleration) from other AVs to evade crashes in the road network (Rahman et al., 2021). The connectivity among these intelligent vehicles makes safe lane changing, overtaking, and car-following decisions. Therefore, AVs have created high expectations in enhancing the safety performance of road networks. Papadoulis et al. (2019) estimated that fully controlled AVs would provide a 90% increase in safety. However, this impact level has not been proved officially due to the lack of data.

As a result, many automotive manufacturers are working on ongoing projects and field operational tests in different road environments (Papadoulis et al., 2019). These trial experiments have confirmed that AVs would initiate a spectrum of revolutionary challenges (Papadoulis et al., 2019). For example, whether the prevailing urban infrastructure and motorway can host the AVs is questionable. Moreover, the inherent challenges emerging due to the interaction between AVs and conventional vehicles during the changeover phase are unclear. Besides, the absence of compatibility among the software from different automakers is uncertain, which might affect their performance at the corridor level (Papadoulis et al., 2019).

Despite real-world experiments, the fleet data for AVs are not readily available to assess their safety benefits (Mohebifard and Hajbabaie, 2020). Therefore, a technique based on micro-simulation is the only alternative technique to estimate AVs' safety benefits for different penetration rates (Almobayedh, 2019). In this study, recent studies used a simulation software to investigate the safety impacts of AVs (Papadoulis et al., 2019; Severino et al., 2021; Sinha et al., 2020). However, the different techniques in the literature to simulate AVs have limitations. Several researchers

---

✉ Corresponding author.
E-mail: dspawar@ce.iith.ac.in

proposed different algorithms and assigned an Application Programming Interface (API) of micro-simulation software (VISSIM) to create an AV environment and assessed the safety benefits (Deluka Tibljaš et al., 2018; Tajalli and Hajbabaie, 2018; Wan et al., 2016). Furthermore, fewer studies calibrated the car-following model parameters without any ground truth to create an AV environment (Bansal et al., 2017; Genders and Razavi, 2016). Moreover, most studies assessed the safety benefits using the default driving behavior implemented in car-following model, which may not estimate real-world AV behavior (Tajalli and Hajbabaie, 2018; Mirheli et al., 2018; Letter and Elefteriadou, 2017; Mousavi et al., 2021).

Besides the above limitations, the influence of varying static and dynamic characteristics of vehicles in predicting the safety benefits of AVs is unknown. Traffic in developing countries such as India is not homogeneous and the influence of heterogeneous traffic on the safety performance of AVs in the network is questionable. None of the past studies (except few studies) used the driving behavior models from the CoExist project for the AV simulation in PTV VISSIM that are modified and verified using real-field AV data (VISSIM, 2018; Sukennik, 2018).

In summary, several studies did assumptions to assess the safety benefits of AVs using crash data. Most of the studies used algorithms to develop an AV behavioral framework on the API interface of VISSIM and in several studies, the parameters for the car-following model were calibrated in order to calculate the safety benefits of AVs. However, all these studies performed simulations under homogeneous conditions, and they solely took into account passenger cars while evaluating the safety benefits of AVs. With these opportunities, by utilizing the calibrated and validated AV driving behaviours from VISSIM, this study explores the safety advantages of AVs to find the reduction in number of conflicts and travel time under heterogeneous conditions using three driving logics. Two driving logics were adopted from VISSIM default driving behavior of AVs and the third driving logic was adopted from the study by Atkins (2016). With this motivation, this study aims to estimate the performance (travel time) and safety impacts (conflicts) because of the introduction of AVs in heterogeneous conditions using the micro-simulation software (PTV VISSIM) with default driving behavior models of AVs recommended by CoExist project.

2 Literature review

Previous studies estimated the influence of AVs on the outcomes of performance and safety benefits using historical crash data and simulation data. Therefore, this study categorized the literature based on the type of data used to estimate the safety benefits of AVs: (1) safety evaluation based on historical accident statistics and (2) safety evaluation using simulation.

2.1 Safety impact evaluation based on historical accident statistics

Based on the available historical accident statistics, Hayes (2011), Silberg et al. (2012); and Fagnant and Kockelman (2015) attempted to assess the potential safety benefits because AVs were introduced to the road network. AVs can potentially reduce the crashes that occur due to human error, and Fagnant and Kockelman (2015) assumed that 90% of the crashes due to human error are reduced as the AVs are self-driving. As per the National Highway Traffic Safety Administration, AVs with full V2V communication will prevent 439,000 to 615,000 road accidents annually (FMVSS, 2016). On the other hand, studies comparing the execution of AV to the execution of automated technologies in rail or aviation found that crashes are as low as those in rail and aviation, eventually leading to 1% (Hayes, 2011). Even though these studies provided useful insights about the potential safety benefits of hosting the AVs, the assumptions made in predicting the benefits may limit the reliable outcomes.

2.2 Safety impact based on micro-simulation software

Recent studies used simulation and the optimization-based approach to investigate the safety benefits arising from the significant difference in the driving behavior of AVs (Curto et al., 2021; Rahman et al., 2019). The majority of studies used the aforementioned approach to establish the

behaviour structure to simulate the driving behaviour of AVs at various penetration rates on a large scale in order to estimate the potential safety benefits. Table 1 summarizes the recent studies that used simulation to predict the safety benefits of AVs. For instance, Arvin et al. (2021) considered two levels (low and high) of automation to simulate the AVs at different rates in conjunction with conventional vehicles: (1) The type of car-following model utilized for this study was Wiedemann for AVs with a low level of automation, and (2) the Adaptive Cruise Control (ACC) was utilized for AVs with a low level of automation. The authors used open-source simulation software "VENTOS" to evaluate the Time-to-Collision (TTC) and extract the conflicts number. Their research found that at a 100% AV penetration rate, collisions are completely avoided. On the other hand, Park and Smith (2012) developed an algorithm using PARAMICS to reduce the merging-related conflicts for the upstream ramp merging areas.

Several studies used different simulation softwares such as CORSIM, SUMO, VISSIM, and MATLAB and developed different algorithms to predict the safety benefits (Abdel-Aty et al., 2020; Genders and Razavi, 2016; Jin et al., 2014). However, most of the studies simulated AV driving behaviour utilizing VISSIM. For example, Virdi et al. (2019) used micro-simulation software (VISSIM) and SSAM software output to evaluate the safety benefits of AVs. The authors proposed an algorithm "Virdi CAV control protocol" to build the behavioral framework of AVs, and for simulating the human driving behavior, default parameters (car-following model) were used. Their study results showed that the collisions were completely eliminated when all vehicles on the road network are fully automated. For autonomous intersection control, Li et al. (2013) developed an algorithm in the extension API interface of VISSIM and transferred the trajectories data generated from VISSIM into the SSAM software to predict the types of conflicts. Based on the approach designed for AV intersection safety evaluation, the authors observed a single traffic conflict for 100% penetration rate. However, the designed approach is applicable only for intersections, and the approach is not transferrable at the corridor or network level. Fyfe and Sayed (2017) proposed a Cumulative Travel Time (CTT) algorithm in VISSIM API interface to estimate AVs' safety benefits at signalized intersections. Their study results reported a 40% reduction in rear-end crashes when all the vehicles are fully automated. Furthermore, Papadoulis et al. (2019) developed a program for lateral decision-making and longitudinal control of AVs on highways. The authors concluded that the collisions were reduced (90%–94%) at 100% Market Penetration Rates (MPR). Zhang et al. (2021) examined the influence of AVs on motorway crash pots. The authors developed a car-following model for AVs, and

Table 1 Summary of existing literature based on AV

Ref.	Car following model	Software	Study area	MOE	Collision reduction (MPR - 100%)
Guériau et al. (2020)	Proposed driving behavior - wiedemann	SUMO	Motorway	Safety	58%
Rahman (2021)	Proposed driving behavior - wiedemann	VISSIM	Arterial	Safety	100%
Rahman et al. (2019)	Proposed driving behavior - wiedemann	VISSIM	Arterial	Safety	34%
Papadoulis et al. (2019)	CoEXist Project	VISSIM	Freeway	Safety	94%
Letter and Elefteriadou (2017)	Default	CORSIM	Freeway	Traffic Operations	—
Mousavi et al. (2021)	Default	VISSIM	Highway	Safety	100%
Genders and Razavi (2016)	Modified driving behavior	PARAMICS	Arterial	Safety	—
Fyfe and Sayed. (2017)	Proposed driving behavior-wiedemann	VISSIM	Freeway	Safety	40%
Wan et al. (2016)	Default	PARAMICS	Arterial	Traffic Operations	—
Tajalli and Hajbabaie (2018)	Default	VISSIM	Arterial	Safety	—
Arvin et al. (2021)	Default	SUMO	Freeway	Safety	100%
Jin et al. (2014)	Default	SUMO	Arterial	Traffic Operations	—
Sinha et al. (2020)	Proposed driving behavior - wiedemann	VISSIM	Freeway	Safety	100%
Severino et al. (2021)	Proposed driving behavior - wiedemann	VISSIM	Flower Roundabout	Safety	—
Khashayarfard and Nassiri (2021)	CoExist	VISSIM	Unsignalized Intersection	Safety	93%
Curto et al. (2021)	Proposed driving behavior - wiedemann	VISSIM	Roundabout	Safety	64%
Atkins (2016)	Modified driving behavior	VISSIM	Freeway	Traffic Operations	—
Morando et al. (2018)	Default	VISSIM	Signalized Intersection	Safety	65%

used the default Weidemann car-following model for conventional vehicles. Two scenarios were developed: (1) In the first scenario, AVs have the ability to change lanes, and (2) in the second scenario, AVs were constrained to managed lanes. The study results showed that there was an increase in conflicts up to 300% in the first scenario, while the conflicts reduced from 63 to 0 in the second scenario.

Previous studies altered the default car-following model parameters in micro-simulation software to simulate the behaviour of AVs (Atkins, 2016; Bansal and Kockelman, 2017). For example, Morando et al. (2018) modified the parameters in VISSIM for the car-following model, and investigated the potential for crashes using SSAM at roundabout and signal head intersections. Their study results demonstrated that when the MPR of the AVs increased, the overall number of crashes reduced.

3 Methodology

3.1 Study area

This study selected an Outer Ring Road (ORR) of Hyderabad for the microsimulation of AVs. It is an 8-lane divided multi-expressway with access control and has 19 access points (Hyderabad Metropolitan Development Authority (HMDA, 2012)). It has a lane width of 3.5 m and a design speed of 120 km/h. The salient features of the ORR were obtained from the official site of the HMDA. In this study, the road segment selected from Exit 5 to Exit 18 (as shown in a solid red line) is approximately 44 km in length (Fig. 1).

Fig. 1 Selected stretch on ORR (Google map, 2022).

3.2 Vehicle composition data

The vehicle composition included 79% of trucks and 21% of cars (Ghosh et al., 2020). The peak hour volume (3,600) was calculated by referring to the ORR traffic analysis using a regression model (Leela et al., 2018).

3.3 Simulation setup

The ORR network was built as per the existing road geometric designs in the microsimulation software VISSIM as shown in Fig. 2a. The decision to use VISSIM (Version 2020) was made because of its potential to accurately model vehicle decision, infrastructure, and complex vehicle interaction (Abdel-Aty et al., 2020). The road segment has trumpet (Fig. 2b) and rotary grade-separated interchanges (Fig. 2c).

In Figs. 2b and 2c, the average speed reduction ranges from 40 to 60 km/h were provided on the ramps of grade-separated interchanges to avoid drifting. This study used conventional (car and Heavy Goods Vehicle (HGV)) and autonomous vehicles (car-AV and HGV-AV) for this simulation. The Desired Speed Distribution (DSD) for each vehicle type was considered in this simulation range from 60 to 100 km/h. When other vehicles or

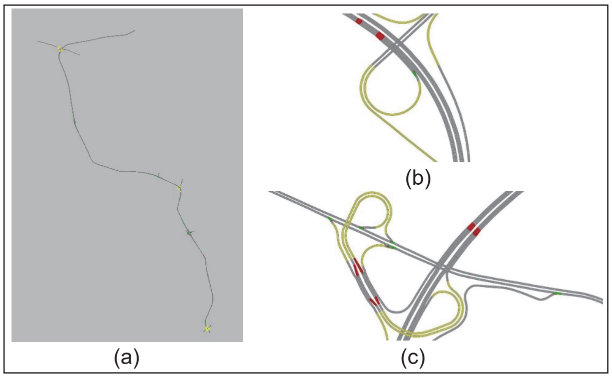

Fig. 2 Study stretch for the simulation (a) outer ring road (ORR) network, (b) trumpet interchange, and (c) loop interchange.

obstacles are not affecting the speed of the vehicles, the speed distribution is known as DSD. The AV penetration rates selected for this study are 0%, 10%, 30%, 50%, 70%, 90%, and 100%. Case study was done for different traffic flow conditions (free flow, intermediate flow, peak off, and peak hour). However, the three driving logics were effective only during high peak hour conditions. During other traffic flow conditions, the simulation showed similar results for all three driving logics. Also the reduction percentages in total travel time and conflicts were not reduced in all three driving logics.

The peak hour traffic volume was simulated for one hour time interval. The time interval selected for the simulation ranged from 0 to 4,200 s. The initial 600 s of the simulation period was considered a warm-up period to allow the interaction between vehicles in the network.

3.4 Calibrated driving behavior parameters

The car-following model's parameters for both conventional and autonomous vehicles should be modified to account for the heterogeneous traffic condition. The parameters for conventional vehicles (Large Goods Vehicle (PCV) and HGV) in this study were taken from an earlier study are presented in Table 2 (Ghosh et al., 2020). The parameters of the driving behavior for the AVs are calibrated and validated based on the driving behavior data obtained from AVs in the field operational tests of CoEXist project (Sukennik, 2018; VISSIM, 2018). CoEXist work included three driving logics in the PTV VISSIM based on their principles and capabilities.

In this study, three AV driving logics were considered, two types of AV driving logics from PTV VISSIM (cautious and all-knowing) and another type of AV driving logic, "Atkins" (Atkins, 2016). In all-knowing driver logic, the vehicle predicts the behavior of other road users using vehicle-to-infrastructure (V2I) and V2V communication technologies. The vehicle has profound awareness and predictive capabilities, leading mainly to smaller gaps for all man-oeuvres and situations. A kind of cooperative behaviour is expected. The vehicle maintains smaller safety distance with the preceding vehicles. In cautious driving logic, the vehicle observes the road code and always adopts a safe behaviour. The brick wall stop distance is always active, but the vehicle will maintain larger safety distance with preceding vehicles. In a Atkins driving logic, following AVs can modify their behavior depending on the characteristics of the front vehicle according to a methodology created by Atkins. AVs may potentially have more aggressive acceleration and number of the observed vehicles because of vehicle connectivity technology. The vehicles will maintain much smaller gap with preceding vehicles than the all-knowing driving logic. The difference between all-knowing, Atkins, and cautious driving logic is the safety distance maintained between the vehicles. According to VISSIM software, both cautious and Atkins driving logic maintain a very shorter safety gap but cautious driving logic maintains a larger safety gap. The simulation was conducted as a 3 (driving logics) × 7 (penetration rates) by a total of 21 scenarios.

3.5 Simulation data

For each penetration rate, the simulation run was repeated five times. After the simulation runs, two data files were obtained from VISSIM. One includes the total travel time of all vehicles on the whole network, which is a direct output result, and another is a vehicle trajectory file collected for every simulation run. Since the simulation is repeated five times for each penetration rate, the average values of travel time and the number of conflicts from the trajectory files were determined.

3.6 SSAM setup

The software named SSAM was created by the Federal Highway Administration (FHWA) to locate crashes from trajectory files (Gettman et al., 2008). The SSAM was primarily utilized to gather the different types of conflicts that occurred in the network. Traffic conflicts were identified using TTC and Post-encroachment Time (PET) thresholds in SSAM software. For safety assessment, several studies examined at a default TTC criterion of 1.5 s (Curto et al., 2021; Papadoulis et al., 2019; Rahman et al., 2019; Tajalli and Hajbabaie, 2018). Similar to that, the default TTC criterion of 1.5 s was taken into account in this study. The vehicle trajectory files obtained from the VISSIM were used as an input file for SSAM. The output results from the SSAM provide the number of conflicts for conflict types such as rear-end, crossing, and lane changing.

4 Analysis of travel time and conflicts

4.1 Travel time

The average total travel time of all the vehicles in the road network was obtained from the five simulation runs at each penetration rate of AVs. The simulation runs were made for each of the driver logics, "all-knowing", "Atkins", and "cautious", and the travel time variation at different penetration rates is presented in Fig. 3. AVs maintain shorter headways, which decrease the total travel

Table 2 Calibrated parameters for conventional and automated vehicles

Parameter	CAR	HGV	AV-Cautious	AV-All Knowing	AV-Atkins
CC0 Standstill distance (m)	1.24	1.78	1.5	1	0.5
CC1 Headway time (s)	0.6	0.64	1.5	0.6	0.5
CC2 Following variation (m)	2.15	3.8	0	0	0
CC3 Controls the deceleration process	−7.87	−5.43	−10	−6	−6.0
CC4 Negative following threshold	−1.07	−1.03	−0.1	−0.1	0
CC5 Positive following threshold	−1.01	1.3	0.1	0.1	0

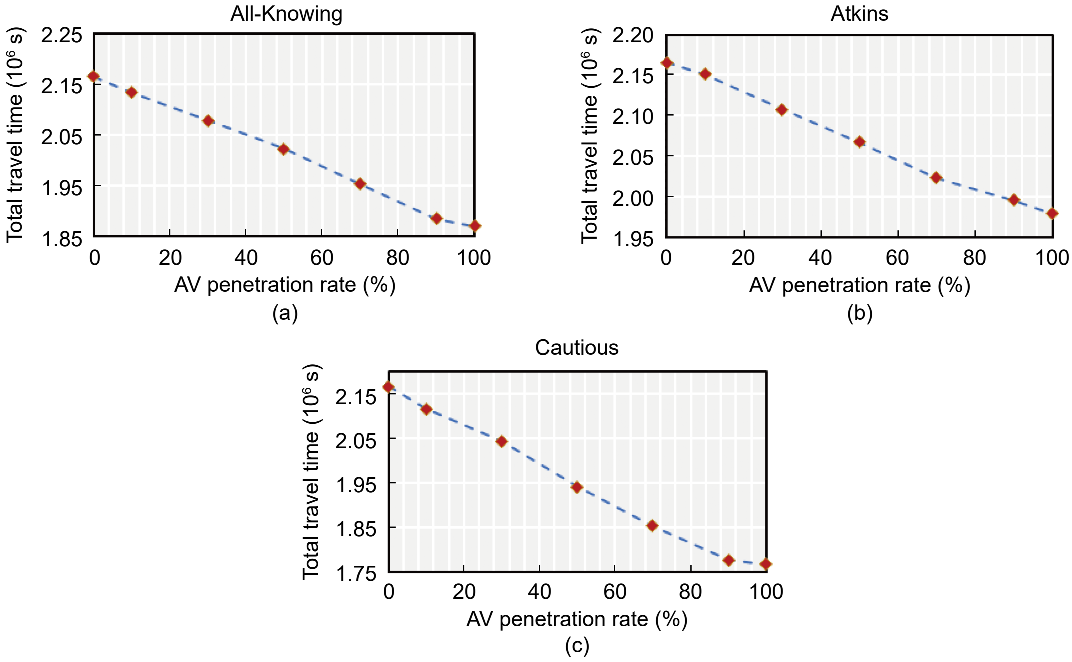

Fig. 3 Total travel time for whole network: (a) All-Knowing, (b) Atkins, and (c) Cautious.

time with the increase in MPR. From Figs. 3a–3c, it can be observed that the three driving logics showed a similar decrement pattern in travel time, i.e., the travel time decreases with an increase in AV penetration rate. However, it can be seen that the reduction in travel time for "cautious" was found to be steeper in comparison to "all-knowing" and "Atkins" driving logics. The simulation was done for three different variables (Atkins, cautious, and all-knowing driving logic). As discussed in the methodology section, the simulation was done for 5 runs because the network stretch is 40 km long and the VISSIM and SSAM software could not analyze the result for higher simulation run. This is one of the reasons that the One-way Analysis of Variance (ANOVA) was executed with less sample size.

Kolmogorov–Smirnov (K–S) test was used to determine the normality of the travel time data for each driving logic at a 5% level of significance. Table 3 shows the K–S test results as well as descriptive statistics for the travel time data. The normal distribution parameters (mean and standard deviation (SD)) were estimated using the maximum likelihood method.

The standard deviation of travel time for cautious driving logic is more due to larger headway gaps maintained between vehicles. The SD from the mean's relative variability is shown by the coefficient of variation (COV). When compared to all-knowing (0.055) and Atkins (0.035), the greater COV for cautious (0.077) suggests greater variation in travel time. The travel time distribution was negatively skewed for all-knowing, whereas positively skewed for cautious and Atkins. The mean value confirmed more travel time for Atkins (~2,000,000) and all-knowing (~2,000,000) compared to cautious (1,950,907.1). To determine the statistically significant difference in mean travel time at different driver logics, a ANOVA test was used.

The hypothese are formulated as follows: H_0 is the mean of travel time for different driving logics that are statistically the same; H_1 is the mean of travel time for different driving logics that are statistically different.

ANOVA tests revealed a statistically significant difference between the group means of travel time for different driving logics. Thus, the test rejected the null hypothesis claiming that the means of the travel time for the three AV driving logics are the same. However, Tukey's honestly significant difference (TSD) test was performed to identify the pairwise difference in mean travel time for different driving logics. Table 4 presents the pairwise difference in group means of travel time for driving logics at a 5% significance level. Cautious and Atkins driving logic showed a statistically significant difference in mean travel time $p < 0.05$). In both AV groups (Atkins-all-knowing and cautious-all-knowing), the pairwise difference in mean travel time was insignificant.

Table 3 Descriptive statistics and K–S test results for travel time

AV type	Mean	SD	Max (s)	Min (s)	COV	Skewness	K–S value	*p*-value
Atkins	2,069,737.4	73,401.74	2,197,111	1,941,594	0.03	0.11	0.11	0.70
All-Knowing	2,015,633.8	111,611.3	2,197,111	1,838,288	0.05	−0.00	0.13	0.54
Cautious	1,950,907.1	151,001.2	2,197,111	1,725,356	0.077	0.11	0.12	0.58

Table 4 Tukey's HSD test results for travel time

AV group	95% confidence interval		*p*-value
	Lower	Upper	
Atkins-All knowing	−13,041.04	121,248.35	> 0.13
Cautious-All knowing	−131,871.32	2,418.06	> 0.06
Cautious-Atkins	−185,974.98	−51,685.59	< 0.01

Fig. 4 displays the percentage decrease in total travel time for each driving logic for peak hour volume at different penetration rates. At AV 50% penetration rate, the percentage reduction in travel time for Atkins and all-knowing is approximately half the percentage of total travel time reduction in cautious (10%) driving logic. For Atkins and all-knowing driver logics, the difference in the percentage reduction of the travel time is marginal with the increase in the MPR. When the AV penetration rate reaches 100%, cautious driving logic (19%) showed a higher percentage reduction in travel time compared to the other two driving logics.

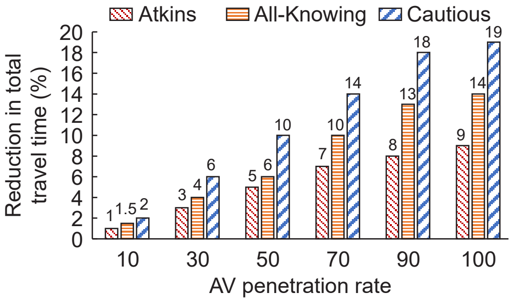

Fig. 4 Percentage reduction in total travel time.

In VISSIM, it was observed that all the vehicles (including three AV driving behaviors) traveled at lower speeds while entering/exiting the ramps to avoid the runoff on the curved roads. The Atkins and all-knowing AVs travel at shorter headways while merging/diverging the ramps, and the through traffic movement slows down till merging traffic clears, which increases the travel time of the entire network. However, in the case of AV cautious due to the larger headway, the through traffic movement was not affected, thereby reducing travel time for the entire network.

4.2 Traffic safety

The reduction in the total conflict points at each MPR for all the three driving logics is shown in Figs. 5a–5c. As the MPR of AVs increases, the overall number of conflicts declines. In the all-knowing driving logic, the difference in the reduction of conflicts is marginal when the MPR of AVs increases from 0% to 30%. However, above 30%, the reduction in the number of conflicts was drastic at higher MPR. In the case of Atkins, the general pattern showed a decrement in the number of conflicts with the increase in the MPR. The cautious driving logic significantly reduced the number of crashes at each penetration rate among the three driving logics. Table 5 presents the descriptive statistics for the conflict data and the K–S test results for normality at the 5% level of significance. The standard deviation of conflicts for cautious driving logic is higher due to larger headway gaps maintained between the vehicles at different MPRs. The COV for cautious driving logic (0.131) is high, which specifies more variation in conflicts compared to Atkins (0.086) and all-knowing (0.081). The conflict data were negatively skewed for cautious and Atkins, whereas positively skewed for all-knowing. The mean value of conflicts confirmed lower conflicts for cautious (273) in comparison to Atkins (~290) and all-knowing (~292).

The hypotheses formulation for ANOVA is as follows: H_0 is the mean conflict for different driving logics that are statistically the same; H_1 is the mean conflict for different driving logics that are statistically different.

At a 5% level of significance, the ANOVA results revealed a statistically significant difference in the mean conflicts for the three driving logics (Table 6). The pairwise significant difference between cautious and Atkins driving logics showed a statistically significant difference between each other in the mean conflicts

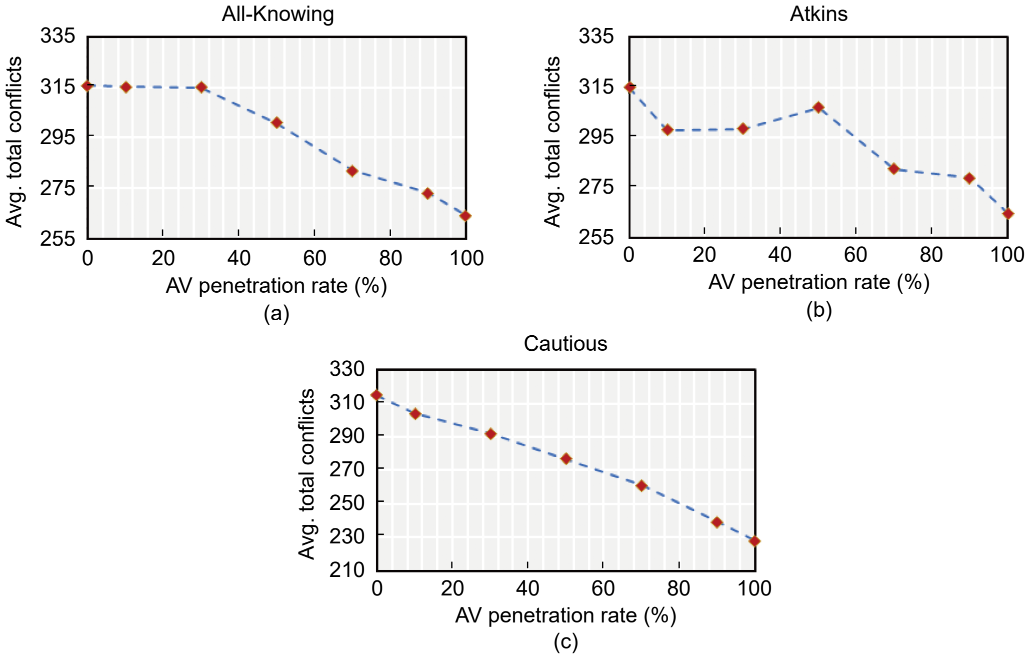

Fig. 5 Reduction of average total conflicts: (a) All-Knowing, (b) Atkins, and (c) Cautious.

Table 5 Descriptive statistics and K–S test results for conflicts

AV type	Mean	SD	Max (s)	Min (s)	COV	Skewness	K–S value	*p*-value
Atkins	293.08	23.85	328	253	0.08	−0.05	0.07	0.97
All-Knowing	292.25	23.32	328	223	0.08	0.59	0.09	0.92
Cautious	273.97	36.05	328	194	0.13	−0.40	0.11	0.73

Table 6 Tukey's HSD test results for conflicts

AV group	95% confidence interval		p-value
	Lower	Upper	
Atkins-All knowing	−17.516 54	15.859 400	> 0.99
Cautious-All knowing	−35.802 26	−2.426 315	> 0.02
Cautious-Atkins	−34.973 69	−1.597 743	> 0.02

($p < 0.05$). Similarly, cautious and all-knowing driving logics showed a statistically significant difference in mean conflicts. However, the pairwise difference in the mean conflicts for Atkins and all-knowing was insignificant.

The percentage reduction in the conflicts for the three driving logics at each penetration rate is shown in Fig. 6.

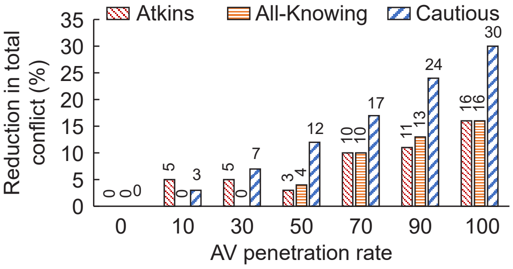

Fig. 6 Percentage reduction of total conflicts for different penetration rates.

Above 50%, all the three driving logics showed a general increment in the reduction of conflicts; however, it can be seen that, below 50% MPR, the conflicts are low, and also pattern (increment/decrement) is not observed. The difference in the percentage reduction of conflicts for Atkins and all-knowing above 30% MPR is marginal; however, cautious driving logic showed the highest percentage reduction in the conflicts compared to the other two driving logics.

5 Results and discussion

This study investigates the performance and safety benefits of of AVs at different MPRs. The parameters for the car-following model for human driving behavior were adopted from the real field study made in India by Ghosh et al. (2020). In addition, the simulation was performed for mixed traffic conditions. Fig. 7 shows the comparison of percentage reduction in total conflicts at AV 100% penetration rate for previous studies and the present study. In this study, the simulation was performed for heterogeneous traffic conditions, and this might be one of the reasons for the lower percentage reduction in conflicts compared to previous studies.

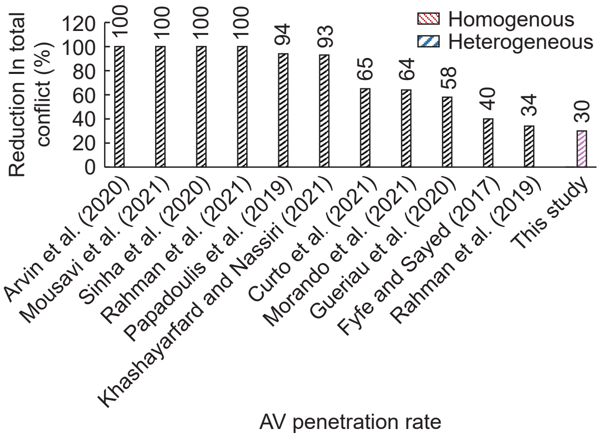

Fig. 7 Comparison of reduction in conflicts at AV 100% with previous studies.

The study results showed that the travel time and conflicts were reduced in all the three cases of the driving logics. Furthermore, the results show that the AV cautious driving logic is much effective at different penetration rates, because the cautious driving logic follows a larger safety distance to avoid collision with the preceding vehicles and it follows road conditions to obey the rules. However, both the Atkins and all-knowing follow short safety distance. Therefore, the reduction of travel time and collision is less due to the complex road.

6 Conclusions and future research directions

This study analyzed the performance (reduction in travel time) and safety benefits (conflicts) of AVs on an expressway using the microsimulation software VISSIM. To evaluate the safety benefits of AVs at various penetration rates, three different types of AV driving logics were taken into consideration. The parameters for conventional vehicles and peak hour volume were adopted from previous studies. The simulation was run for different penetration rates to determine the reduction of travel time and the number of conflicts for all three driving logics. The VISSIM-generated output trajectory files were used to analyze the total conflicts using SSAM. ANOVA test was conducted to investigate the significant difference in travel time and the number of conflicts that existed between the three driving logics. The following inferences are listed based on the simulation results:

1) The percentage reduction in travel time decreases with the increase in MPR of AVs. From statistical analysis, AV-Cautious has a significant reduction in travel time when compared to the other two driving logics.

2) The percentage reduction in the number of conflicts decreases with the increase in MPR of AVs. Amongst all three driving logics, cautious showed a significant reduction when compared to other two driving logics in the number of conflicts.

Findings of this study from observation conclude that for the lower penetration rates (0%–50%), the reduction in travel time and conflicts was not effective; however, above 50% MPR of AV, the reduction in travel time and conflicts was noticeable.

This study has fewer limitations that can be addressed in future research work.

1) This study adopted calibrated and validated parameters of the car-following model for AVs under homogenous traffic conditions. Further studies can recommend the parameters for the car-following model for heterogeneous traffic conditions based on field experiments to simulate the AV environment.

2) Most of the studies simulated passenger cars to evaluate the safety benefits of AVs. Future studies can assess the safety benefits for a proportion of different vehicle types at different MPRs in the network.

3) The AV behavior may change depending on the road network, peak hours, or congested highways. Also, the length of the road network might change the behavior of AVs. In the future study, all three AV driving logics should be tested for different road interchanges, road network lengths, and congested highways.

In this study, AV behavior was modeled by using VISSIM's default car-following model parameters (CoExist project). However, there is definitely space to build more accurate car-following model parameters for AVs and calibrate them using actual data under heterogeneous conditions. In India, the facilities for implementing AVs were in early stages in current situations. Also, the AV vehicles are not readily available to conduct a real field experiment to find out the calibrated parameters for AVs. Therefore, calibrating the AV parameters according to Indian condition is quite challenging in current conditions. In future, this study results can be compared with the calibrated parameters for Indian conditions.

Replication and data sharing

The data generated during VISSIM simulation can be accessed at https://drive.google.com/drive/folders/1iQT3Iu_t8lUE_oP1Hdp6yRlgr1rNBbmu.

Acknowledgements

This work was supported by the DST National Mission Interdisciplinary Cyber-Physical Systems (NM-ICPS) and Technology Innovation Hub on Autonomous Navigation and Data Acquisition Systems: TiHAN Foundations at Indian Institute of Technology (IIT) Hyderabad.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

Abdel-Aty, M., Wu, Y., Saad, M., Rahman, M. S., 2020. Safety and operational impact of connected vehicles' lane configuration on freeway facilities with managed lanes. Accid Anal Prev, 144, 105616.

Almobayedh, H. B., 2019. Simulation of the impact of connected and automated vehicles at a signalized intersection. Ph.D. Dissertation. Dayton, Ohio, USA: University of Dayton.

Arvin, R., Khattak, A. J., Kamrani, M., Rio-Torres, J., 2021. Safety evaluation of connected and automated vehicles in mixed traffic with conventional vehicles at intersections. J Intell Transp Syst, 25, 170–187.

Atkins, W. S., 2016. Research on the impacts of connected and autonomous vehicles (CAVs) on traffic flow. Stage 2: Traffic modelling and analysis technical report. SO13994/3.

Bansal, P., Kockelman, K. M., 2017. Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies. Transp Res A, 95, 49–63.

Curto, S., Severino, A., Trubia, S., Arena, F., Puleo, L., 2021. The effects of autonomous vehicles on safety. In: AIP Conference Proceedings, 110013.

Deluka Tibljaš, A., Giuffrè, T., Surdonja, S., Trubia, S., 2018. Introduction of autonomous vehicles: Round abouts design and safety performance evaluation. Sustainability, 10, 1060.

Fagnant, D. J., Kockelman, K., 2015. Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. Transp Res A, 77, 167–181.

FMVSS, N., 2016. Vehicle-To-Vehicle Communication Technology For Light Vehicles. FMVSS No. 150. https://www.iihs.org/media/716de1d2-7e8c-48bf-947e-7cfd20bd1259/w5q4PA/RegulatoryComments/comment_2017-04-10.pdf

Fyfe, M., Sayed, T., 2017. Safety evaluation of connected vehicles for a cumulative travel time adaptive signal control microsimulation using the surrogate safety assessment model. In: Transportation Research Board 96th Annual Meeting, 17, 01651.

Genders, W., Razavi, S. N., 2016. Impact of connected vehicle on work zone network safety through dynamic route guidance. J Comput Civ Eng, 30, 04015020.

Gettman, D., Pu, L., Sayed, T., Shelby, S. G., 2008. Surrogate safety assessment model and validation: Final report. FHWA-HRT-08-051.

Ghosh, T., Roy, S. K., Gangopadhyay, S., 2020. Assessment of multilane highway capacity through simulation process by considering the effect of behavior of driver of a vehicle. J Inst Eng India Ser A, 101, 589–596.

Google Maps, 2022. Selected stretch on outer ring road. Sourced from Google Maps. URL: https://www.google.com/maps/@17.4734522,78.3630423,11.72z?entry=ttu

Guériau, M., Cugurullo, F., Acheampong, R. A., Dusparic, I., 2020. Shared autonomous mobility on demand: A learning-based approach and its performance in the presence of traffic congestion. IEEE Intell Transp Syst Mag, 12, 208–218.

Hayes, B., 2011. Leave the driving to it. Amer Scientist, 99, 362.

Hoogendoorn, R., van Arerm, B., Hoogendoom, S., 2014. Automated driving, traffic flow efficiency, and human factors. Transport Res Rec, 2422, 113–120.

Hyderabad Metropolitan Development Authority (HMDA), 2012. https://www.hmda.gov.in

Jin, Q., Wu, G., Boriboonsomsin, K., Barth, M., 2014. Platoon-based multi-agent intersection management for connected vehicle. In: 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013), 1462–1467.

Khashayarfard, M., Nassiri, H., 2021. Studying the simultaneous effect of autonomous vehicles and distracted driving on safety at unsignalized intersections. J Adv Transp, 2021, 1–16.

Leela, K. S. S., Krishna, P. V., Chandram, M., 2018. Outer ring road traffic analysis and prediction. In: National Conference On Trends In Science, Engineering & Technology by Matrusri Engineering College & IJCRT, 322–326.

Letter, C., Elefteriadou, L., 2017. Efficient control of fully automated connected vehicles at freeway merge segments. Transp Res C, 80, 190–205.

Li, Z., Chitturi, M. V., Zheng, D., Bill, A. R., Noyce, D. A., 2013. Modeling reservation-based autonomous intersection control in VISSIM. Transport Res Rec, 2381, 81–90.

Malaghan, V., Pawar, D. S., 2022. A short-term naturalistic driving study on predicting comfort thresholds for horizontal curves on two-lane rural highways. J Transp Eng A, 148, 04022045.

Ministry of Road Transport and Highways (MORTH), 2020. Road accidents in India 2020. https://morth.nic.in/road-accident-in-india

Mirheli, A., Hajibabai, L., Hajbabaie, A., 2018. Development of a signal-head-free intersection control logic in a fully connected and autonomous vehicle environment. Transp Res C, 92, 412–425.

Mohebifard, R., Hajbabaie, A., 2020. Effects of automated vehicles on traffic operations at round abouts. In: 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC), 1–6.

Morando, M. M., Tian, Q., Truong, L. T., Vu, H. L., 2018. Studying the safety impact of autonomous vehicles using simulation-based surrogate safety measures. J Adv Transp, 2018, 1–11.

Mousavi, S. M., Osman, O. A., Lord, D., Dixon, K. K., Dadashova, B., 2021. Investigating the safety and operational benefits of mixed traffic environments with different automated vehicle market penetration rates in the proximity of a driveway on an urban arterial. Accid Anal Prev, 152, 105982.

Papadoulis, A., Quddus, M., Imprialou, M., 2019. Evaluating the safety impact of connected and autonomous vehicles on motorways. Accid Anal Prev, 124, 12–22.

Park, H., Smith, B. L., 2012. Investigating benefits of IntelliDrive in freeway operations: Lane changing advisory case study. J Transp Eng, 138, 1113–1122.

Rahman, M. H., Abdel-Aty, M., Wu, Y., 2021. A multi-vehicle communication system to assess the safety and mobility of connected and automated vehicles. Transp Res C, 124, 102887.

Rahman, M. S., Abdel-Aty, M., Lee, J., Rahman, M. H., 2019. Safety benefits of arterials' crash risk under connected and automated vehicles. Transp Res C, 100, 354–371.

Severino, A., Pappalardo, G., Curto, S., Trubia, S., Olayode, I. O., 2021. Safety evaluation of flower round about considering autonomous vehicles operation. Sustainability, 13, 10120.

Silberg, G., Wallace, R., Matuszak, G., Plessers, J., Brower, C., Subramanian, D., 2012. Self-driving cars: The next revolution. White paper, KPMG LLP & Center of Automotive Research, 9, 132–146.

Singh, S., 2015. Critical reasons for crashes investigated in the national motor vehicle crash causation survey. No. DOT HS 812 115.

Sinha, A., Chand, S., Wijayaratna, K. P., Virdi, N., Dixit, V., 2020. Comprehensive safety assessment in mixed fleets with connected and automated vehicles: A crash severity and rate evaluation of conventional vehicles. Accid Anal Prev, 142, 105567.

Sukennik, P., PTV Group, 2018. D. 25 Micro-Simulation Guide for Automated Vehicles.

Tajalli, M., Hajbabaie, A., 2018. Distributed optimization and coordination algorithms for dynamic speed optimization of connected and autonomous vehicles in urban street networks. Transp Res C, 95, 497–515.

Virdi, N., Grzybowska, H., Waller, S. T., Dixit, V., 2019. A safety assessment of mixed fleets with connected and autonomous vehicles using the surrogate safety assessment module. Accid Anal Prev, 131, 95–111.

VISSIM, 2018. PTV VISSIM 10 User Manual. https://usermanual.wiki/Document/Vissim20102020Manual.1098038624.pdf

Wan, N., Vahidi, A., Luckow, A., 2016. Optimal speed advisory for connected vehicles in arterial roads and the impact on mixed traffic. Transp Res C, 69, 548–563.

World Health Organization (WHO), 2018. Global status report on road safety 2018. Geneva: World Health Organization, 2018.

Yue, L., Abdel-Aty, M., Wu, Y., Wang, L., 2018. Assessment of the safety benefits of vehicles' advanced driver assistance, connectivity and low level automation systems. Accid Anal Prev, 117, 55–64.

Zhang, H., Hou, N., Zhang, J., Li, X., Huang, Y., 2021. Evaluating the safety impact of connected and autonomous vehicles with lane management on freeway crash hotspots using the surrogate safety assessment model. J Adv Transp, 2021, 1–14.

Nalin Kumar Sekar is a Ph.D. student in the School of Mechanical Engineering at Vellore Institute of Technology. He obtained his M.S. degree in Vehicle Engineering from Kaunas University of Technology, UK. He obtained his B.E. degree in Mechanical Engineering at St. joseph's College of Engineering. His research interests include emerging vehicle technologies and road safety.

Vinayak Malaghan is a post-doctoral research fellow in the School of Civil, Structural, and Environmental Engineering at Trinity College Dublin (TCD). Before joining TCD, he worked as an Institute postdoctoral fellow at Indian Institute of Technology (IIT) Hyderabad on emerging vehicle technologies (advanced driving assistance systems), emphasising road safety using instrumented vehicle data. He earned Joint Ph.D. degree from the IIT Hyderabad and Swinburne University of Technology, Australia. During his doctoral and postdoctoral research studies, he got introduced to and consequently developed interest and expertise in multiple research areas, i.e., geometric design, driver behaviour, naturalistic driving study, traffic operations and safety, data science, statistical methods, machine learning, road safety and CAVs. Before joining Ph.D. studies, he worked as a Deputy Engineer in a consultancy firm named Lea Associates South Asia Pvt. Ltd. He received his M.S. degree in Transportation Engineering from Birla Institute of Technology and Science (BITS), Pilani (Pilani campus), India and B.S. degree in civil engineering from Visvesvaraya Technological University, India.

Digvijay S. Pawar is an Associate Professor in Transportation Systems Engineering in the Department of Civil Engineering, IIT Hyderabad. Prior to joining IIT Hyderabad in 2016, Digvijay was a senior research associate in IIT Bombay from 2015. He received his Ph.D. degree in Transportation Systems Engineering from IIT Bombay, India in 2015. He completed his B.S. degree in Civil Engineering from Walchand College of Engineering, Sangli, India in 2009. His research predominantly focuses on traffic operations and safety, human factors and highway geometric design with emphasis on Intelligent Transportation Systems (ITS) and Naturalistic Driving Studies. His contributions in developing Intelligent Transportation Systems (ITS) for improving driver and pedestrian safety at uncontrolled intersections are noteworthy. He has played a key role in designing and implementing several ITS technologies and establishing testbed at IITH for studies on autonomous vehicle systems.