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Can Autonomous Vehicles Improve the Traffic Flow Efficiency in Heterogeneous Traffic Environments? A Simulation-based Investigation

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ABSTRACT: Autonomous vehicles promise numerous benefits for future mobility, including reduced stress for drivers, congestion, emissions, and energy consumption, as well as increased safety, road capacity, and efficient parking management. A detailed literature review revealed the scarcity of research on connected and autonomous vehicles in developing countries. The present study employs microscopic simulation to analyse the impact of autonomous vehicle penetration in the mixed driving environment prevalent in India. The simulation was carried out by modelling a typical autonomous vehicle (AV) and introducing it to various parts of a road network, including midblock sections of highways and expressways, signalised and unsignalized intersections, and allowing it to operate along with conventional vehicles. The parameters in VISSIM were adjusted to closely mimic the Indian traffic operations. Simulation results indicated that uninterrupted facilities of highway and expressway midblock sections showed an improvement in throughput with the penetration of AV into the conventional stream of vehicles. While the capacity of the expressway increased by almost 87%, the increase was by 21% for the highway sections. At the same time, the penetration of AVs into facilities with interrupted traffic, such as signalised and unsignalized at-grade intersections, decreased the traffic throughput. While the reduction in capacity was marginal for signalised intersections (1.3%), there was a significant reduction for unsignalized intersections (13-18%). The drop in capacity at interrupted facilities could be attributed to the cautious nature of AVs in comparison to conventional traffic.

KEYWORDS: Autonomous Vehicles; Heterogeneous Traffic; Intersections; Midblock Sections; VISSIM

1. INTRODUCTION

The development of transportation systems and technologies has played a major role in the evolution of cities and economic systems. The advancements in wireless communication, digital processing, and sensing technologies over the past few decades have led to significant developments in transportation systems engineering, to the extent that the operation of autonomous vehicles has become a reality. An autonomous vehicle (AV), connected and autonomous vehicle (CAV), driverless car, self-driven car or robotic car is a vehicle that can sense its environment and move safely with little or no human input. Present-day connectivity technology allows vehicles to communicate with other vehicles (through vehicle-to-vehicle communication) and infrastructure (through vehicle-to-infrastructure communication). Consequently, the driver's decision-making aspects would be enhanced through connectivity. This improvement in connectivity has shed light on the execution of traffic management for connected autonomous vehicles. The development of such a connected environment serves three primary purposes: improving safety, enhancing mobility, and reducing emissions. The majority of studies in the area of autonomous vehicles are based on traffic conditions prevalent in developed countries, where traffic is generally homogeneous. However, the behaviour of traffic and drivers in developing countries is much different from elsewhere. Hence, it is vital to study the effect that autonomous vehicles will have on the traffic movements of developing countries like India.

The present research aims to make an inroad in this direction by investigating the variation in the characteristics of heterogeneous traffic flow with the introduction of autonomous vehicles through microscopic simulation in PTV VISSIM. For this, traffic flow on different road sections (midblock sections and intersections) was simulated to replicate Indian traffic conditions best. This was achieved by updating the default traffic parameters of VISSIM using calibrated values from previous studies, and by varying the share of autonomous vehicles, the effect of autonomous vehicle penetration on mixed traffic conditions in India was investigated. The study explores the changes in traffic patterns resulting from the introduction of varying percentages of autonomous vehicles into the conventional traffic of interrupted and uninterrupted highway sections.

2. RESEARCH GAP AND CONTRIBUTION

The future of connected and autonomous vehicles is likely to be a technology with excellent potential for development, but the effects may not be realised in a short time span. A complete shift from the current transportation scenario to a fully automated driving environment will require a significant transitional period of social acceptance. The adaptation of autonomous vehicles to a mixed traffic environment, comprising human-driven vehicles and other connected vehicles, during the aforementioned transition is crucial in achieving complete automation. Even when fully autonomous vehicular streams are possible, pedestrians and cyclists must be able to traverse the road facilities safely. Hence, analysing the heterogeneous traffic with varying compositions of autonomous and human-driven vehicles is necessary. This will enable the authorities to understand how AV penetration levels could

alter the traffic pattern and adopt timely measures to mitigate the changes in traffic flow patterns.

3. BACKGROUND LITERATURE

A detailed survey of various literature discussing the effects of autonomous vehicles in different traffic conditions was conducted to formulate the need and objective of the present study.

3.1. AVs in transportation systems

Talebpour and Mahmassani (2016) comprehensively investigated the role of communication in operating CAVs and the interaction between autonomous vehicles, human-driven vehicles with connectivity and human-driven vehicles without connectivity. The simulation results showed that throughput increases with the market penetration of CAV, preventing shockwave formation and propagation. Berrada and Leurent (2017) summarised the main modelling works on transportation systems involving AVs that were published in the academic literature by the end of 2016. They quoted that full automation from conventional vehicles will be achieved by 2040, while Todd Litman (2024) opined that the same will be achieved only by 2060. Hence, this fairly long transition period from the current scenario to full automation underscores the importance of research on traffic that incorporates a mix of conventional vehicles and CAVs.

Dresner and Stone (2007) proposed measures to modify the system of intersection control, based on a reservation system, to accommodate both conventional vehicles and autonomous vehicles using existing infrastructure. Thomas and Trost (2017) investigated the feasibility of implementing AV as a public transportation system or as a feeder system to public transportation systems in developing countries, such as India. They opined that rather than adopting a commercial AV designed for developed countries, an AV could be prototyped and developed, which would run on the critical roads of developing countries with slight modifications.

3.2. Effect of AVs' penetration levels

Several studies have also explored the effect of CAV's penetration level into the conventional traffic stream to draw significant benefits. In the report prepared by Atkins (2016) for the Department for Transportation, the potential impacts of CAV on traffic flow and road capacity in the UK road network were investigated. The simulation-based methodology employed in this study revealed that a high penetration of CAVs is necessary to achieve significant benefits in terms of traffic throughput and travel time. Even a 25% CAV penetration had a negligible impact on the traffic flow. Ye et al. (2018) analysed the impact of CAVs on traffic flow under various penetration rates based on acceleration and velocity distribution. On simulating a 10 km two-lane road segment using a Cellular Automaton (CA) model with various penetration percentages of CAVs, it was observed that the introduction of CAVs in mixed flow would boost smooth driving as the stop-and-go traffic will be greatly eased when CAV penetration rate reaches 40 to 50%. Yao and Friedrich (2019) proposed a strategy that operates CAVs to drive in platoons led by manually driven CAVs to reduce travel delays and improve social acceptance of CAVs. They suggested that when the CAV penetration level is low (<40%), a CAV platoon should operate globally. However, when CAV penetration is high, it should be designed to operate locally by designating a certain share of CAVs as potential leaders. Bhargava et al. (2020) analysed the impact of simulated CAV Freight (CAV-F) in improving the traffic throughput at Dartford Crossing tunnel, UK. The study was based on the simulation results of VISSIM, and they showed that CAV-F, alongside conventional Light Goods Vehicles, increased the overall traffic flow by 33%.

3.3. Summary

Despite the extensive efforts in the literature to analyse the impacts of autonomous vehicles on the driving environment, there is still a need for more comprehensive studies. From the available research on autonomous vehicle flow, it is evident that studies on the development of required infrastructure and traffic flow management for autonomous vehicles in developing countries are scarce. Due to their lack of well-organised road infrastructure, developing countries have largely fallen behind in the technological race for automation at the technological and government levels. Lane change behaviour and the effects of autonomous vehicle penetration in developing countries, where heterogeneous traffic lacks lane discipline, need to be explored in the immediate future to enable road users to experience the advantages of autonomous driving during the transition period to full automation.

4. METHODOLOGY

Field studies of autonomous vehicles require thousands of kilometres of testing before implementing an autonomous vehicle flow management, which may not be feasible in the present scenario. Microsimulation packages are the most effective alternative to address this challenge. The present study uses VISSIM to simulate the traffic flow on various road segments in India. These include uninterrupted flow facilities, such as midblock sections of highways and expressways, and interrupted facilities, such as signalised and unsignalized at-grade intersections. However, there is a distinct difference between the default simulation model in VISSIM and the traffic flow observed on Indian roads. Hence, it is essential to modify the default parameters in VISSIM to simulate how vehicles move and negotiate on Indian roads.

The default network behaviour of right-hand traffic in VISSIM was changed to left-hand traffic, as found in India. To match the undisciplined lane behaviour of Indian vehicles, the vehicles were allowed to take any position in the lane, diamond queuing was enabled, and lateral and overtaking behaviour was modified to allow vehicles to overtake from both sides with free selection of lanes. As the vehicle characteristics in VISSIM did not match those of Indian vehicles, the default values of vehicle dimensions, desired speed distribution, acceleration and deceleration functions, and driving behaviour in VISSIM were replaced with values from previous research that were calibrated for Indian conditions. Typical traffic compositions, as found across different interrupted and uninterrupted road segments in India, were adopted to simulate the traffic flow.

VISSIM provides three types of AV models: AV cautious, AV normal and AV aggressive. Among the three, the AV aggressive model is programmed with shorter headways, faster acceleration, and tighter gaps, both when following and when standing still, compared to the other two models. Hence, this aggressive driving model was adopted for the autonomous vehicle model created to study its penetration effects in Indian conditions. Furthermore, the research assumed that the simulated AV works as a stand-alone system, without the opportunity to communicate with infrastructural elements. A three-dimensional vehicle model was created for AV by adopting the car as the base category. The vehicle's features and dimensions include a length of 4.761 m, a width of 2.063 m, and a speed distribution curve that varies linearly from 60 km/h to 80 km/h. Based on the research by Zeidler et al. (2019), the Wiedemann-99 car-following model was used for AV driving behaviour. AV, a human-free driving technology designed for developed countries that follow strict lane

discipline, was allowed to occupy only the middle position in any lane, along with disabled diamond queuing and overtaking capabilities within the same lane. A lower value is used for standstill distance (CC0) and gap time distance (CC1) as the reaction time of the driver can be neglected. The values adopted for CC0 and CC1 were 1m and 0.6 s, respectively.

After the proper calibration of the VISSIM model, traffic flow with a conventional vehicle composition was simulated for a duration of 3600 s following a 120 s warm-up period. Subsequently, further simulations were performed by replacing the proportion of cars in conventional vehicle composition by penetrating different percentages (25, 50, 75 and 100) of AVs. Data collection points were placed at suitable locations for each road facility as per the analysis requirements. Simulation runs were repeated for ten different random seeds in VISSIM, and the output data were exported to MS Excel for further processing and analysis. The number of vehicles generated was converted into the equivalent number of passenger cars using the corresponding Passenger Car Equivalents (PCE), and the capacities of each facility were determined accordingly.

The following sections provide details about the modified parameters adopted in VISSIM to replicate the traffic operations on specific road segments in India.

4.1. Midblock Segment of a Highway

A four-lane divided highway was chosen, similar to a rural inter-urban highway in India with uninterrupted flow conditions. The speed distribution curves and acceleration and deceleration rates for each vehicle type were modified to reflect the vehicular characteristics in India, based on data obtained from the study by Mehar et al. (2014). A typical traffic composition found on the interurban highways in India was adopted for simulation. The properties of the simulated traffic flow are given in Table 1.

As an uninterrupted facility, the Wiedemann-99 car-following model was chosen as the driving behaviour by inputting calibrated values for CC0 and CC1. CC2 to CC9 has little influence, as per the sensitivity analysis by Mehar et al. (2014). Based on vehicle composition and speed distribution, values adopted for CC0 and CC1 were 1.5 m and 0.9 s, respectively. To unify the influence of different vehicles constituting the traffic stream, the vehicles were converted into corresponding passenger car units. For the design of the midblock facility, the concept of area-velocity ratio was adopted for PCE estimation (Chandra and Sikdar, 2000) as given in Eq. (1).

Eq. (1) $$PCE_i = \frac{{}^{Vc}/_{Vi}}{{}^{Ac}/_{Ai}}$$

where,
PCE_i = Passenger Car Equivalent of i^{th} vehicle type
${}^{Vc}/_{Vi}$ = Speed ratio of car to i^{th} vehicle type
${}^{Ac}/_{Ai}$ = Physical area ratio of car to i^{th} vehicle type

Equation 1 was adopted to estimate the PCE values of all vehicle types, including the AVs. By varying the input volumes, different sets of flow and weighted average velocities of various classes of vehicles were obtained. These were used to estimate the density values assuming a linear relationship between speed and density. The peak of the flow-density curve was used to estimate the capacity for a specific simulation run, and the average of these capacities was reported as the facility's capacity. The capacity of the midblock section was computed for different penetration levels of AVs.

4.2. Midblock Segment of an Expressway

A straight and uninterrupted section of a six-lane divided interurban highway was created with three lanes each of 3.5m width in each direction. The dimensions, composition, and parameters adopted for vehicles operating on this stretch were derived from the study conducted by Bains et al. (2012) and are listed in Table 2.

Vehicle type	Proportion (%)	Length (m)	Width (m)	Speed Parameters (km/h)		
				Max.	Min.	Mean
Car	86.3	4.9	1.9	102	78	90
Truck	4.6	8.5	2.5	69	48	60
Bus	3.8	11.4	2.5	93	64	79
Light Commercial Vehicle (LCV)	3.4	6	1.9	80	63	73
Multi-Axle Vehicle (MAV)	1.9	8	3	62	40	53

Table 2. Vehicle parameters and composition

The Wiedemann-99 car-following model best suits the simulation of uninterrupted facilities. Hence, a standstill distance (CC0) of 1 m and a time gap distance (CC1) of 0.9 s were used to calibrate the expressways, replicating mixed traffic conditions in India (Bains et al., 2012). The methodology for PCE estimation and capacity calculation with varying percentages of AVs replacing cars was identical to that adopted for highway midblock sections, as discussed in the previous section.

4.3. Signalized Intersection

A four-legged, signalised intersection was created in VISSIM, with all approaches featuring a four-lane, divided configuration. The dimensions and composition of vehicles given as input in the created network are shown in Table 3.

Vehicle Type	Length (m)	Width (m)	Proportion (%)
Two-wheeler	1.80	0.68	46
Three-wheeler	2.36	1.08	15
Car	4.36	1.97	33
LCV	5.00	2.05	1.5
Bus	11.55	2.69	3.5
Truck	10.21	2.50	1

Table 3. Vehicle dimensions and their proportion in the traffic stream

Vehicle Type	Proportion (%)	Speed Parameters (km/h)			Percentile Speeds (km/h)		Acceleration (m/s²)		Deceleration (m/s²)	
		Max	Min	Avg	15^{th}	85^{th}	Max	Desired	Min	Desired
Car	40	98.8	30.3	63.5	45.2	82.1	2.7	1.3	1.8	1.2
Two-wheeler	17	103.3	34.9	59	36.6	81.5	2.5	1.5	1.7	1.2
Three-wheeler	05	61.4	26.7	43.2	28.6	57.8	1.1	0.9	1.1	0.8
Heavy Vehicle	38	87.4	23.4	47.2	27.6	66.8	2.2	1.6	1.5	0.5

Table 1. Properties of simulated traffic on the highways

The Wiedemann-74 car-following model was used to represent the driving behaviour of the interrupted facility at a signalised intersection. The heterogeneous traffic condition was mimicked by modifying the parameters in VISSIM based on the calibrated values from a previous study (Mathew and Radhakrishnan 2010). It includes an average standstill distance of 1.33 m, with additive and multiplicative components of 0.28 and 0.16, respectively. The minimum lateral distances corresponding to speeds of 0 km/h and 50 km/h for the model were set at 0.3 m and 0.42 m, respectively. The values of desired speed, acceleration, and deceleration for input vehicles, as adopted from the literature (Mathew and Radhakrishnan, 2010), are given in Table 4.

Vehicle Type	Desired Speed (km/h)	Acceleration (m/s²)		Deceleration (m/s²)	
		Max.	Desired	Min.	Desired
Two-wheeler	40	2.49	1.65	1.70	1.19
Three-wheeler	25	1.19	0.89	1.11	0.79
Car	30	1.53	1.19	1.21	0.96
LCV	25	0.79	0.69	1.21	0.59
Bus	20	1.31	0.81	1.43	0.59
Truck	20	0.99	0.81	0.79	0.59

Table 4. Speed, acceleration and deceleration rate adopted for vehicles in VISSIM

At signalised intersections, turning traffic will have a more pronounced effect on the traffic flow than the through traffic. Hence, the simulation study at signalised intersections was carried out in two parts. Firstly, the effect of different penetration rates of AV at signalised intersections catering to only through traffic was studied. A two-phase signal control was adopted for the intersection with a cycle length of 60 s and an amber time and all-red periods of 2 s and 3 s, respectively, per phase. The first phase (30 s green time) allowed mobility on the North-South approach, whereas the second phase allowed access to East-West approaches.

Later, a similar effect was quantified for traffic streams containing both turning and through traffic. A four-phase signal design with a cycle time of 120 s was adopted to control the turning traffic, with each approach having a separate phase with 26 s of green, 2 s of amber and 2 s of all-red period. Varying proportions of left-turn, straight and right-turn combinations of vehicles from each approach were allowed simultaneously.

For the calculation of saturation flow, a constant queue discharge must be maintained during the entire green time. To ensure this, all approaches were loaded with higher traffic inputs in VISSM, so that they were completely saturated throughout the entire simulation period. For each green phase, a start-up loss of 4 s was considered to achieve a stable queue of vehicles, in accordance with common practice. The PCE was directly used as such from the Indian Highway Capacity Manual (IHCM 2017), and this research assumed AVs to have the same PCE as standard cars owing to the absence of performance records in the field. For different combinations of turning proportions of the traffic stream, the proportions of AVs in the vehicle composition were varied, and the output volumes were observed to obtain the saturation flow for each approach.

4.4. Unsignalized Intersection

A priority intersection, configured with a non-priority single-lane street of one-way traffic crossing a two-lane major street highway, is simulated in VISSIM. To reduce the complexity of PCE estimation, all car conditions were simulated on the conflicting traffic stream in the major street by inputting 'car' alone as the vehicle category. These cars were modelled to move at an average speed of 60km/h. The non-priority stream consisted of the vehicle composition as listed in Table 5. The desired speed values and the acceleration and deceleration values for each input vehicle category were the same as those taken in the simulation of signalised intersection (Table 4). Vehicular movements at an unsignalized intersection operating under queuing conditions were simulated.

Once again, the Wiedemann-74 model was chosen as the car following behaviour for the interrupted facility of unsignalized intersection. The additive and multiplicative parameters were set as 0.4 and 0.6, respectively, with an average standstill distance of 0.2 m. The lateral distance between the vehicles was maintained at 0.2 m in stationary conditions and 0.5 m in moving conditions (Mohan and Chandra 2016).

Vehicle Type	Length (m)	Width (m)	Proportion (%)
Two-wheeler	1.80	0.68	45
Three-wheeler	2.36	1.08	15
Car	4.36	1.97	38
LCV	5.00	2.05	2

Table 5. Vehicle dimensions and composition

For analysis, the through traffic from the minor street crossing the major street, as well as the minor street right-turners, were considered separately. The input traffic volume of the conflicting stream was varied to study the corresponding changes in the capacity of the non-priority stream under various levels of AV penetration. The PCE values for unsignalized intersections, as given in the IHCM (2017), were used for this part of the study. AVs and standard cars were assumed to have the same PCE values.

5. RESULTS AND DISCUSSION

In this research, AV penetration was simulated by replacing cars in the conventional vehicle composition with different percentages of AVs, for various road facilities, including midblock sections of a highway and an expressway, as well as signalised and unsignalized intersections. This section presents the analysis of the simulation results.

5.1. Midblock Segment of a Highway

The vehicle inputs were varied in VISSIM from 2000 to 5500 veh/h/direction for each of the ten random seeds, and the flows (in PCE/h) were calculated for each of the simulation runs. This was performed for conventional traffic composition (0% AV) and for vehicle streams, with AV penetration varied through 25%, 50%, 75% and 100%. The capacities were estimated from the peak of the flow-density plots for each of the simulation runs (10 simulations each for 25%, 50%, 75% and 100% AV penetration levels). The average of the peak flows across the simulation runs was considered as the capacity for that respective case. Table 7 presents the average and standard deviation of capacities for highway midblock sections estimated at different penetration levels.

AV Penetration (%)	Capacity (PCE/h)	
	Average	Standard Deviation
0	5865	± 175
25	5980	± 184
50	6220	± 249
75	6835	± 551
100	7085	± 102

Table 7. Average capacity of midblock computed for different penetration levels

Figure 1 illustrates the variation in capacity of the mid-block section with respect to the percentage of AVs penetrating the conventional traffic composition. A second-degree polynomial equation is fitted to the data, yielding an R^2 of 0.967. It is worth noting that for the case with 100% AV (i.e., all cars in the stream are replaced with AVs), the PCEs can be calculated by taking the AV as the base. This will assign PCE for AV as 1, which tends to reduce the capacity (indicated by the orange-coloured data point in Figure 1) compared to other cases where the car was considered the base. Hence, for the sake of comparison and for plotting the trendline, the capacity was recalculated for 100% AV by rerunning the simulation with a negligible proportion of cars. As the percentage penetration of AV (percentage of conventional cars replaced) increases, the capacity of flow generated at the section increases quadratically. This can be attributed to the increased speed and performance characteristics, as well as the lower headway maintained by AVs. There is hardly any instance of acceleration or deceleration of vehicles plying in the uninterrupted midblock section. Hence, AVs can move with a constant speed, usually at higher speeds compared to conventional vehicles, by maintaining a minimum headway between vehicles. A lag caused by the reaction time of human drivers is also absent in AVs. Due to improved reflexes and enhanced speed characteristics, a greater number of AVs can operate safely on the road. The percentage increase in capacity relative to conventional traffic is 1.96% at 25% AV penetration and 20.78% at 100% AV penetration. Hence, it can be inferred that there is a significant increase in the overall capacity of highway mid-block sections with the increase in the AV penetration.

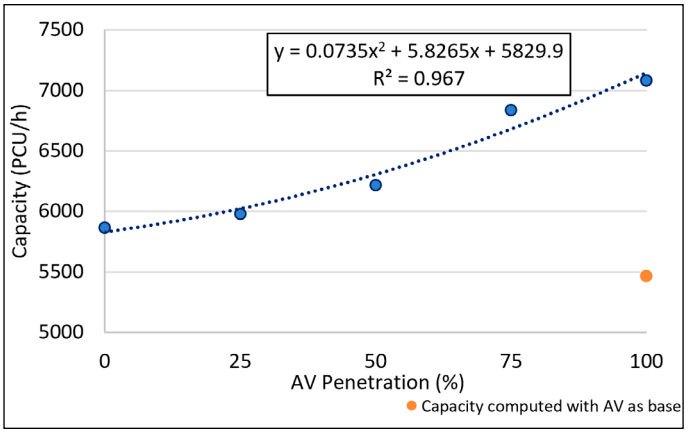


Figure 1. Variation in highway midblock capacities with the increase in AV penetration

5.2. Midblock Segment of an Expressway

AV Penetration (%)	Capacity (PCE/h)	
	Average	Standard Deviation
0	7040	± 964
25	7999	± 1968
50	9636	± 2762
75	11853	± 1522
100	13164	± 1266

Table 8. Average capacity of expressway computed for different penetration levels

The vehicle inputs on the expressway section were varied in VISSIM from 3000 to 9500 veh/h/direction for each of the ten random seeds. The capacities were estimated for conventional traffic composition (0% AV) and vehicle streams having AV penetration varied through 25%, 50%, 75% and 100% by following the same procedure as mentioned in the previous section. Table 8 presents the average and standard deviation of capacities of expressway estimated for different penetration levels.

As mentioned in the previous sections, for the case with 100% AV, the capacity drops when AV is used as the base for finding PCE (indicated by the orange-coloured data point in Figure 2). Hence, for plotting the trendline, the capacity was recalculated for 100% AV by rerunning the simulation with a negligible proportion of cars.

Figure 2 presents the variation in the capacities estimated for different AV penetration levels. The capacity of the section of the expressway considered showed an increase in capacity from 7040 to 13164 PCE/h/direction. This substantial increase in capacity is due to the fact that AV can operate more smoothly with better speeds and a minimum headway, along with other vehicles, which also traverse at the best possible speed and operational characteristics in Indian conditions, given the best level of service conditions available at expressways. The fact that many vehicle types, including two-wheelers and three-wheelers, which usually cause more interruptions in mixed traffic conditions, are absent in the vehicle composition of expressways, justifies the higher capacities obtained compared to the midblock section of highways. From the simulation results, a substantial increase in capacity is observed when all cars are converted to AVs, as the capacity rises by 13.62% from 25% AV penetration to 86.99% at 100% AV penetration.

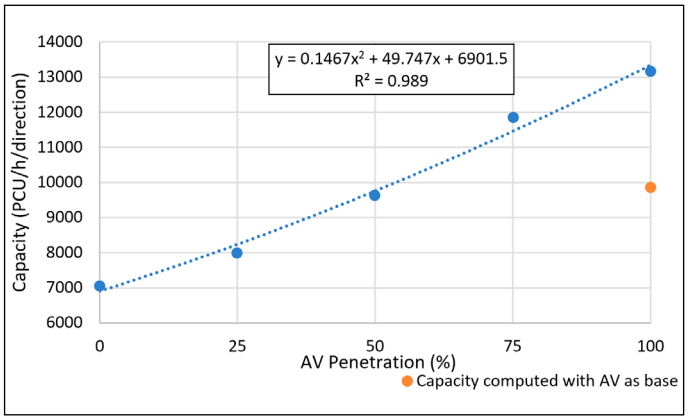


Figure 2. Variation in the capacities of expressway with the increase in AV penetration

5.3. Signalized Intersection

AV Penetration (%)	Saturation Flow (PCE/lane/h of green)	
	Average	Standard Deviation
0	2733	± 76
25	2763	± 76
50	2745	± 6
75	2747	± 51
100	2737	± 80

Table 9. Average saturation flow at signalised intersection with only through traffic

The average saturation flow (in PCE per hour of green time for each lane) for all four approaches of the intersection mentioned in Section 4.3 was estimated by varying the percentage of AV through 25%, 50%, 75%, and 100%. Further simulations were also performed by varying the proportions of turning movement and analysing the impact in each case separately.

The saturation flow at the signalised intersection with no turning traffic was averaged across 10 different random seeds (Table 9), and the variation in saturation flow corresponding to different AV penetrations is shown in Figure 3. It can be seen that the saturation flow decreased only slightly, from 2773 PCE/h/lane for a conventional vehicle composition to 2740 PCE/h/lane at 100% penetration of AV (penetration of AV is defined as the percentage of conventional cars that are replaced), with a percentage reduction of 1.30%.

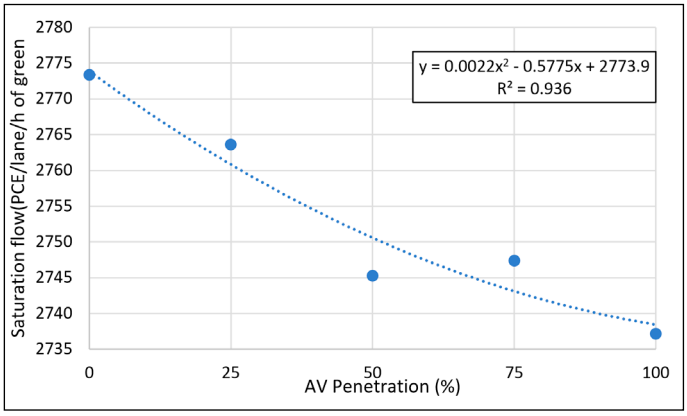


Figure 3. Variation of saturation flow with AV penetration for only through traffic at the signalised intersection

Further simulations were performed by allowing left-turn, through and right-turn share approach operations with a single movement group for each approach. It included equal turning proportions as one case and unequal turning proportions as another, by fixing the proportion of through movement at 60% and varying the right turning movements through 25%, 20%, and 15%. The results of the simulation run were analysed, and the observations made are tabulated in Table 10.

Table 10 shows that the proportions of turning movement have little influence on saturation flow, as the percentage reductions are relatively consistent (around 3.6%). Therefore, it can be concluded that the reduction in saturation flow resulted solely from the increased penetration of AV. Furthermore, it can also be concluded that the penetration of AVs into conventional mixed traffic, although marginal, decreases the saturation flow at a signalised intersection. This differs from the trend observed in mid-block sections of highways and expressways. A close observation of the factors contributing to control delay, such as deceleration to stop, accelerating back to the desired speed, clearance lost time, and start-up lost time, plays a part in the observed trend based on the design made for AV. AVs are primarily designed to incorporate aspects of caution into their operation. During their operation, AVs closely monitor objects, both stationary and moving, in their vicinity to maintain sufficient gaps and avoid collisions. Due to their undisciplined lane behaviour, conventional vehicles in mixed traffic conditions in India often act as obstacles to the smooth movement of AVs at intersections during their start-up and turning movements. Hence, AVs consume more time than conventional vehicles to start up, accelerate to the desired speed, and clear the intersection safely. The presence of AVs, therefore, slightly decreases the saturation flow of this facility.

AV Penetration (%)	Saturation flow (PCE/lane/h of green)			
	Equal Turning proportion	Unequal turning proportion		
		25% right turn	20% right turn	15% right turn
0	2796 (± 52)	2841 (± 29)	2802 (± 102)	2846 (± 19)
25	2777 (± 18)	2813 (± 31)	2776 (± 17)	2805 (± 21)
50	2748 (± 20)	2740 (± 39)	2772 (± 73)	2796 (± 28)
75	2779 (± 18)	2716 (± 58)	2777 (± 18)	2792 (± 15)
100	2717 (± 17)	2715 (± 95)	2746 (± 48)	2785 (± 88)
Percentage reduction in saturation flow	3.69	3.69	3.64	3.59

the values in brackets present the standard deviation

Table 10. Average saturation flow at signalised intersection for different proportions of turning traffic

4.4. Unsignalized Intersection

The capacities of the minor street movements were found through simulation by varying the vehicle input in the priority stream and at different penetration percentages of AVs in the minor traffic composition. The traffic on the major street was simulated to be composed entirely of cars. The capacities for through movement and right-turning movement from the minor street were estimated for different AV penetration levels, as shown in Figures 4 and 5, respectively. For both movements, the capacities were found to vary exponentially with the conflicting major street flow, which aligns with previous research (Mohan and Chandra, 2020). Since left-turners from minor streets do not participate in the gap acceptance process at Indian intersections (Indo-HCM, 2017), this movement was not considered in this study.

The percentage reduction in the capacity of movements from the minor street with the increase in the percentages of AV penetration in traffic was also investigated, corresponding to different major flow conditions. For through traffic from the minor street, the percentage reduction in capac-

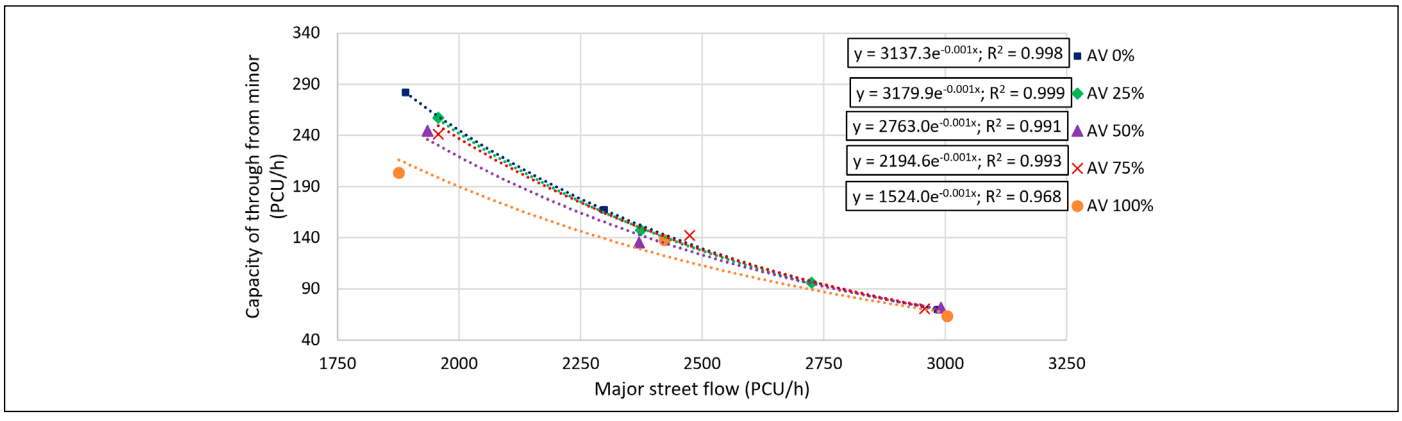


Figure 4. Variation in the capacity of through movements from minor with increase in flow of major street.

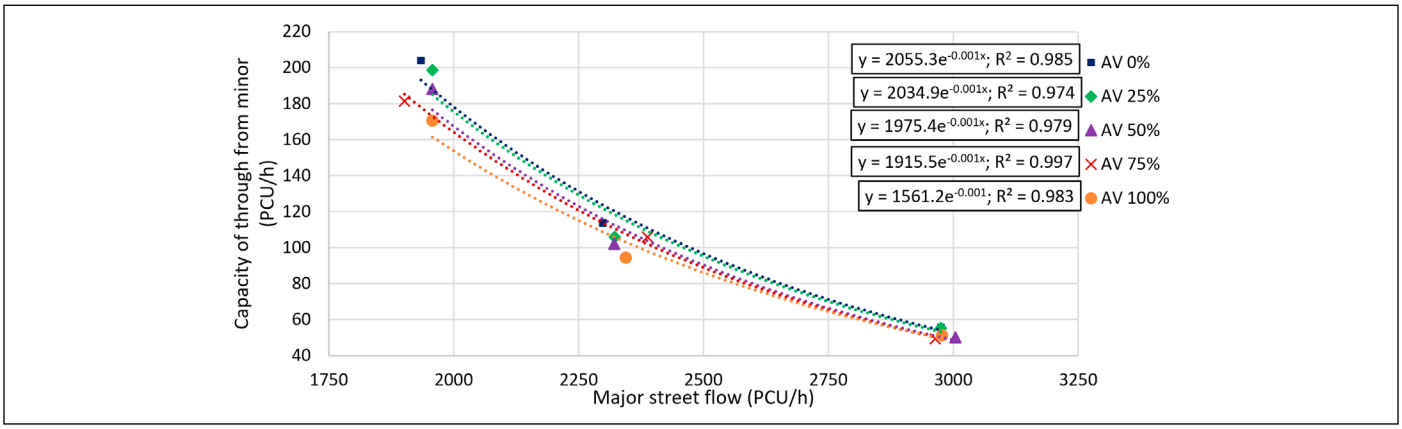


Figure 5. Variation in right turning minor flow with increasing flow in major street.

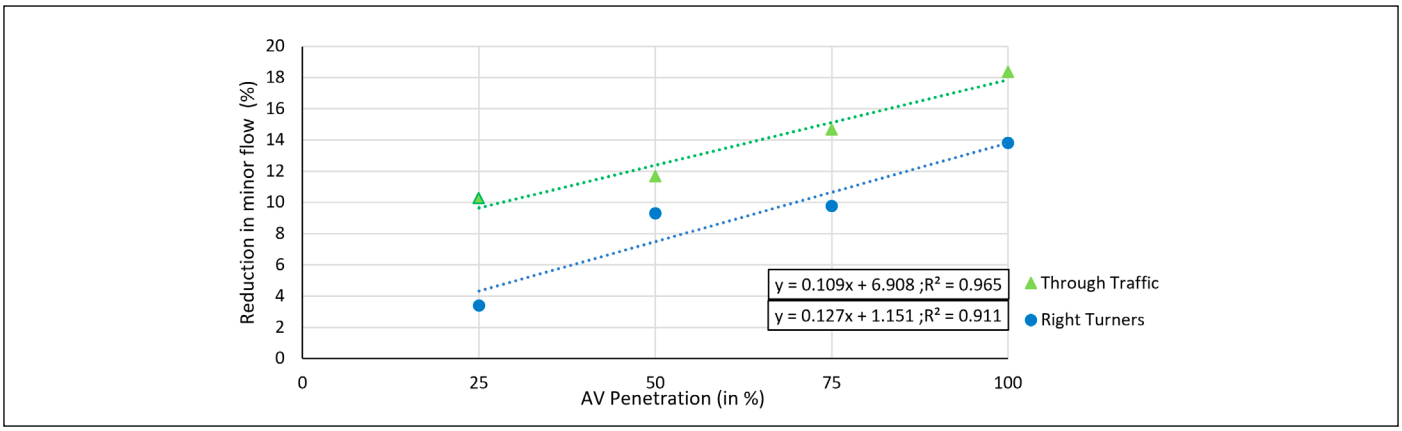


Figure 6. Variation in percentage reduction of capacities of through and right turns from the minor street with increased AV penetration

ity increased from 10.26% at 25% AV to 18.38% at 100% AV. Meanwhile, for right-turning movements, the percentage reduction increased from 3.40% at 25% AV to 13.81% at 100% AV. These variations in the reduction of movement capacities for through and right-turners from minor street are shown in Figure 6.

Major street flow, being the conflicting flow, has relatively higher priority over minor street movement and interferes with the operation of minor street traffic. It can be inferred from the observations that the introduction of AVs into the conventional stream of vehicles does not improve the flow conditions at unsignalized intersections. Instead, the cautious behaviour of AVs makes them more reluctant to accept the gaps in significant flow compared to conventional vehicles, thereby decreasing the movement capacities. It is also worth noting that the forced gap acceptance and priority reversals, common at intersections in developing countries, were not simulated. Such unruly behaviour would further increase the capacity of non-priority movements.

6. CONCLUSIONS

The present research aimed to analyse the effect of Autonomous Vehicle (AV) penetration into conventional mixed traffic streams in the Indian traffic context. Traffic flow at various road segments was simulated using the microsimulation package VISSIM. These road segments include midblock sections of highways and expressways, as well as signalised and unsignalized intersections. The following conclusions were drawn from the outputs of simulation runs.

Uninterrupted facilities, such as mid-block sections of highways and expressways, demonstrated an increase in overall capacity with the increased penetration of AVs. The percentage increase in capacity for the expressway was as high as 86.99%, compared to the 20.78% increase for the highway midblock section. The absence of vehicles that hinder the free movement of other vehicles (like two-wheelers and three-wheelers) on the expressway potentially improved the capacity significantly. Hence, the introduction of AV into uninterrupted facilities under a mixed traffic environment can be recommended due to the enhanced throughput in traffic operation.

Interrupted facilities, such as signalised and unsignalized intersections, showed a decrease in throughput with an increase in the penetration of AVs. In no way did the introduction of AV enhance the capacities of such at-grade intersections, which was due to the stop-and-go movements of vehicles in the mixed traffic environment. Instead, the penetration of cautious AV at intersections can decline the network performance rather than improve it. The reduction in capacity of signalised intersections is relatively less (1.30%) compared to that of unsignalized intersections (13.81-18.38%). Therefore, introducing AV in such facilities is not advisable from the perspective of enhancing traffic performance.

The present study is limited to the analysis of various impacts on traffic performance at isolated facilities, including highways, expressways, signalised and unsignalized intersections, in a mixed traffic environment using a typical AV model. The study was primarily focused on traffic performance, and therefore, the findings of this study should not deter the adoption of AV in developing countries. AV has already been proven to enhance safety on the road, as it can remove human involvement. In the future, the transportation system may become more efficient and safer due to the emergence of new modes of travel, such as autonomous ride-sharing, autonomous buses, and autonomous shuttles.

Moreover, AVs can obtain real-time road warnings and traffic information through the V2X technology, improving driving safety. AVs are also predicted to ease parking scarcity in the city centre.

Although autonomous vehicles are considered the next big revolution in the automobile industry, the transportation infrastructure must be well-equipped to accommodate this transformation. To smooth the transition from partial automation to full automation, further research and experiments should be encouraged, with the expectation of positive returns.

7. LIMITATIONS OF THE STUDY

The study has the following limitations.

- Although the parameters of VISSIM used in this study are adopted from existing literature, the study assumes that these assumptions are valid for the cases simulated.
- The study adopted the default parameters of the AV aggressive model available in VISSIM, as it was impossible to measure and validate the AV behaviour in the field.
- AVs were modelled as independent from each other and devoid of communicating with the infrastructural elements.
- The unruly behaviour of non-priority movements at unsignalized intersections is not modelled in this study.

DATA AVAILABILITY STATEMENT

The parameters adopted in the study for performing the simulations are detailed in the methodology section. However, the raw input files (VISSIM input file, layx file, INP0 file, sig file, etc) could be made available upon request.

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