Road Design Optimisation for Autonomous Vehicles

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ABSTRACT

The rapid progress of Autonomous Vehicle (AV) technology has generated considerable interest in the potential impact on road design. The paper presents the results of research about how the integration of AVs will influence the design and efficiency of road networks. The evaluation utilized a combination of PTV VISSIM software and the Surrogate Safety Assessment Model (SSAM) to construct a network model consisting of a primary arterial road and connecting roads within Dublin City, Ireland. Several scenarios were considered, each exploring various design elements and AV market penetration levels. The study analysed key performance indicators such as throughput volumes, average speed, travel time, vehicle and junction delays, queue length, level of service (LOS), and traffic conflicts to compare the different scenarios. The results revealed that a fully autonomous vehicle fleet led to enhanced throughput volumes and improved junction performance. Surprisingly, a dedicated AV lane did not significantly enhance overall network performance. Instead, a roundabout design emerged as a promising solution, showcasing remarkable improvements in various indicators while also mitigating conflicts compared with other scenarios. Narrower lanes improved travel time and vehicle delay but raised safety concerns due to higher conflict levels. Similarly, as expected, a higher design speed demonstrated better travel speeds. The study underscores the complexity of AV integration and the importance of a balanced approach to optimize safety and efficiency.

Keywords: autonomous vehicles, road design, speed, safety.

INTRODUCTION

The integration of Autonomous Vehicles (AVs) is a rapidly developing concept with the potential to greatly enhance transport safety, efficiency, and accessibility. Traditionally, road design has focused on accommodating Human-Driven Vehicles (HDVs) but by eliminating driver error, which is responsible for about 78% of road accidents (*1*), self-driving cars have the potential to significantly reduce traffic collisions and hence improve safety.

The capabilities and specific needs of AVs demand a thorough reconsideration of established road design methods if secure and seamless integration of AVs is to be delivered within our road systems. It is important to not only incorporate advanced communication technologies like Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I), but also to make adaptations to traditional design features such as sight distance, lane configuration, and intersection design. Research has shown that AVs exhibit faster perception reaction times (PRT) compared to human drivers (*2*), and this presents opportunities for narrower lanes, reduced sight distances, and increased speed limits.

There is currently a limited understanding of the precise road design requirements needed to effectively accommodate AVs. This study seeks to address this gap by investigating the effects on road safety and performance of highway design alterations intended to accommodate AVs such as lane width, dedicated AV lanes, design speed and intersection design on efficiency and safety, at different AV market penetration levels. Due to limited real-life AV data, the study relied on simulation, using VISSIM traffic modelling software, to evaluate the traffic conditions across the modelled scenarios.

The next section of the paper will cover a review of the literature and the methodology will then be presented. Results and discussion will follow while concluding remarks and future recommendations will bring the paper to a close.

BACKGROUND

The primary objective of the highway design process is to create a safe, efficient, and functional road system that accommodates the intended traffic volumes and vehicle types, while taking into account factors like speed, sight distance, turning movements, and traffic flow. To enable the use of self-driving cars, reassessing key transport planning tools such as land use measures, transportation demand management, transportation system management, and road infrastructure expansion to effectively accommodate them is important (*3*).

The widely adopted Policy on Geometric Design of Highways and Streets (Green Book) puts the human driver's perception-response time (PRT) at 2.5s (*4*). Recent studies, however, indicate that with the elimination of the human driver, the PRT could be as low as 0.25s in a fully autonomous vehicle fleet (*5*) which has implications for stopping sight distances (SSDs). While designing highways for AVs, the limits for the length and radius of vertical curves could be more lenient compared to those for HDVs (*6*).

To provide a comprehensive analysis of the current and potential future performance of AVs, it is important to consider both the existing documented AV performance and its anticipated evolution. In highly complex environments, the AV system's decision-making process may require more time, resulting in longer SSDs. Conversely, advancements in technology and system optimization may lead to shorter SSDs for AVs in the future (*6*). Other research, however, underscores the importance of considering the effects of varying automation levels when designing roadways (*7*). Driver assistance and partial/conditional automation systems place higher demands on geometric design from a safety perspective. Intini et al. (*8*) finds that human-based requirements may change in the design of roads for automated vehicle native roads, leading to more relaxed prescriptions for design alignments, speeds, and sight distance.

The design of intersections plays a critical role in ensuring the overall functionality and safety of a road network. AV approach speed at crossing skewed intersections tends to be high especially when the design speed is greater than 70km/h, showing that the requisite SSD is higher than the current AASHTO criteria, and therefore, for safe AV operations, AV approach speed needs to be controlled (*2*). Other research highlights that AV-oriented road designs, such as implementing smaller curves, reduced SSD, and narrower lanes, may introduce challenges for human drivers and potentially increase the risk of road accidents as well as delay (*9*). Additionally, the removal of traffic signals could worsen traffic conditions and add complexity to the road network. While separating AV from non-AV traffic is a possible remedy, cautions with this approach might necessitate the creation of exclusive lanes and the construction of extra bridges or underpasses (*9*). This could result in elevated costs and introduce additional complexity to the road infrastructure, potentially undermining the expected advantages of AVs, including enhanced traffic flow and fuel conservation. The use of Next-Generation Interchange Control (NIC) showed significant potential to improve the efficiency of highway interchanges (*10*).

In terms of safety, skewed intersections have an influence on the safety and Operation Design Domain (ODD) of AVs, particularly on the side with acute-angle approaches, due to complexities in sensor detection (*2*). A substantial knowledge gap was identified regarding the safety impact of interactions between AVs and vulnerable road users in urban areas (*9*). Additionally, AVs necessitate greater lateral clearance for curve sections, stressing the need for designers to be vigilant about potential safety risks arising from delays in updating information by on-board sensors, particularly when the vehicle is traveling at high speeds (*11*).

As AVs are expected to have precise steering and accurate lane tracking systems (*12*), then current lane widths may not be necessary. However, lane width reduction during the transition period may not work with mixed fleets with varying levels of automation. In such cases, it could be more practical to designate dedicated lanes for high-level AVs (*13*). The NCHRP Project 20-102 suggests using exclusive dedicated lanes at 20%–45% market penetration, and no dedicated lanes at over 50% market penetration (*14*).

Assisted driving or partially automated systems introduce a need for more intricate and safety-focused geometric design considerations (*7*). This is because these systems still entail driver engagement and necessitate access to essential information and conditions for vehicle control. Consequently, road design must factor in the constraints of these systems, ensuring drivers have adequate visibility, comfort, and stability to operate safely. Additionally, Advanced Driver-Assistance System (ADAS)-enabled AVs possess the capability to lessen the necessary lateral clearance for vehicle swing during turns and manoeuvres. This ability stems from their precise detection of the vehicle's surroundings and precise trajectory adjustments, potentially resulting in improved road capacity, congestion alleviation, and enhanced road safety and efficiency (*11*).

Transitioning from human-driven vehicles (HDVs) to AVs may necessitate changes in roadway design and related research needs to be done in mixed traffic streams and complex driving conditions (*15*). This study seeks to help address this gap by investigating the effects on road safety and performance of highway design alterations intended to accommodate AVs. The study aims to add to the literature on the potential benefits and challenges associated with incorporating AVs into our transportation system, ultimately informing decisions to enhance the integration of AV technology.

METHODOLOGY

The overall approach to the methodology is presented in Figure 1 and the following sections cover model development, data collection, traffic characteristic definition and scenario development.

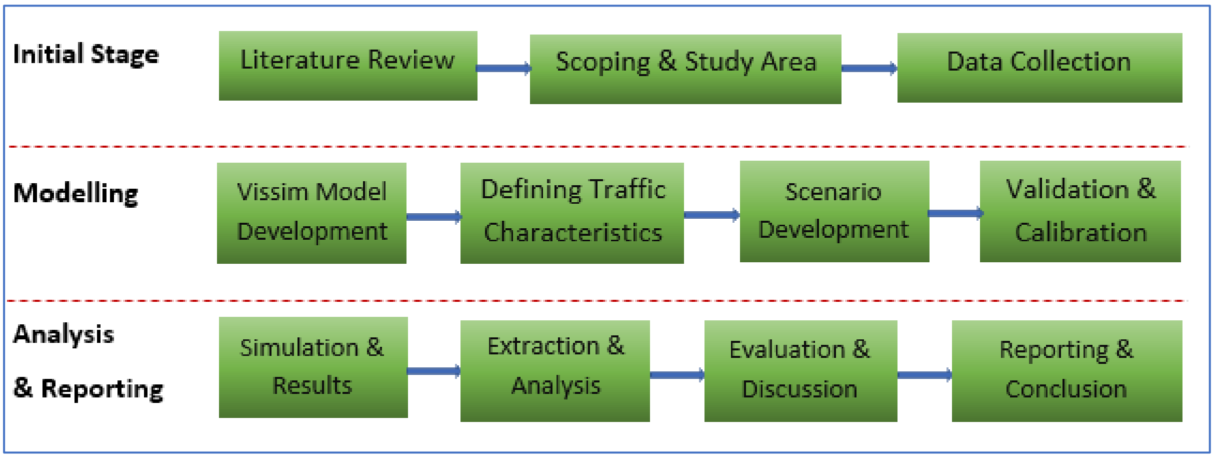

Figure 1. Methodology approach

Modelling

VISSIM model

A VISSIM model was developed for the microsimulation. VISSIM is a widely used microscopic traffic simulation software developed by Planung Transport Verkehr GmbH (*16*) Group. It is designed to model and simulate complex traffic scenarios, including urban and highway networks, to analyse traffic flow, congestion, and various performance indicators. The model set-up stage involved establishing links, connectors, and signal heads, as well as assigning nodes to accurately represent the road network. Vehicle travel time measurements and data collection points were also integrated into the model to gather relevant outputs. Initial traffic flow and demand parameters were set within the VISSIM model, incorporating vehicle inputs, target speeds, and route decisions to simulate real-world scenarios.

Subsequently, scenario development was carried out, with a separate model built for each scenario under study. This allowed for the examination of different design elements and AV market penetration levels. Calibration involved adjusting various parameters within the VISSIM model, including assigned vehicle speeds, lane change behaviour, routing, and conflict areas, to accurately reflect real-world traffic conditions.

Surrogate Safety Assessment Model

The study also utilised the 2017 update (version 3.0) of the Surrogate Safety Assessment Model (SSAM) developed by the Federal Highway Administration of the US Department of Transportation (*17*). SSAM operates by extracting vehicle trajectories from the path files generated by VISSIM (.trj file extension), specially designed for SSAM, and for each pair of conflicting vehicles, categorizes the conflicts based on their conflict angles. This allows for a detailed analysis of the conflicts and, subsequently, provides an indicator of the safety situation within the network for each scenario (*18*).

Definition of the Study Network

The modelled network (in Figure 2) was selected so as to encompass a range of complexities including multi-lane highways, bus lanes, signalised intersections and roundabouts. It consisted of one major urban arterial, the Naas Road, which is a 3-lane dual carriageway, with two lanes designated for regular traffic and one lane for buses. The 2.36km (1.5 mi) scoped section includes the intersection with the Long Mile-Nangor Road, a 2-lane dual carriageway with no designated bus lanes. Additionally, the network included segments of connecting neighbouring roads, namely Turnpike Road, Robinhood Road, Kylemore Road, and Walkinstown Avenue, all of which are single carriageways with 3.5m wide lanes. The selected network was chosen because it provides a direct connection to Dublin's main orbital motorway (M50) and also offers access to a significant residential area, making it an essential link in the transportation network. To facilitate optimal vehicle interactions, minor roads were also integrated into the network.

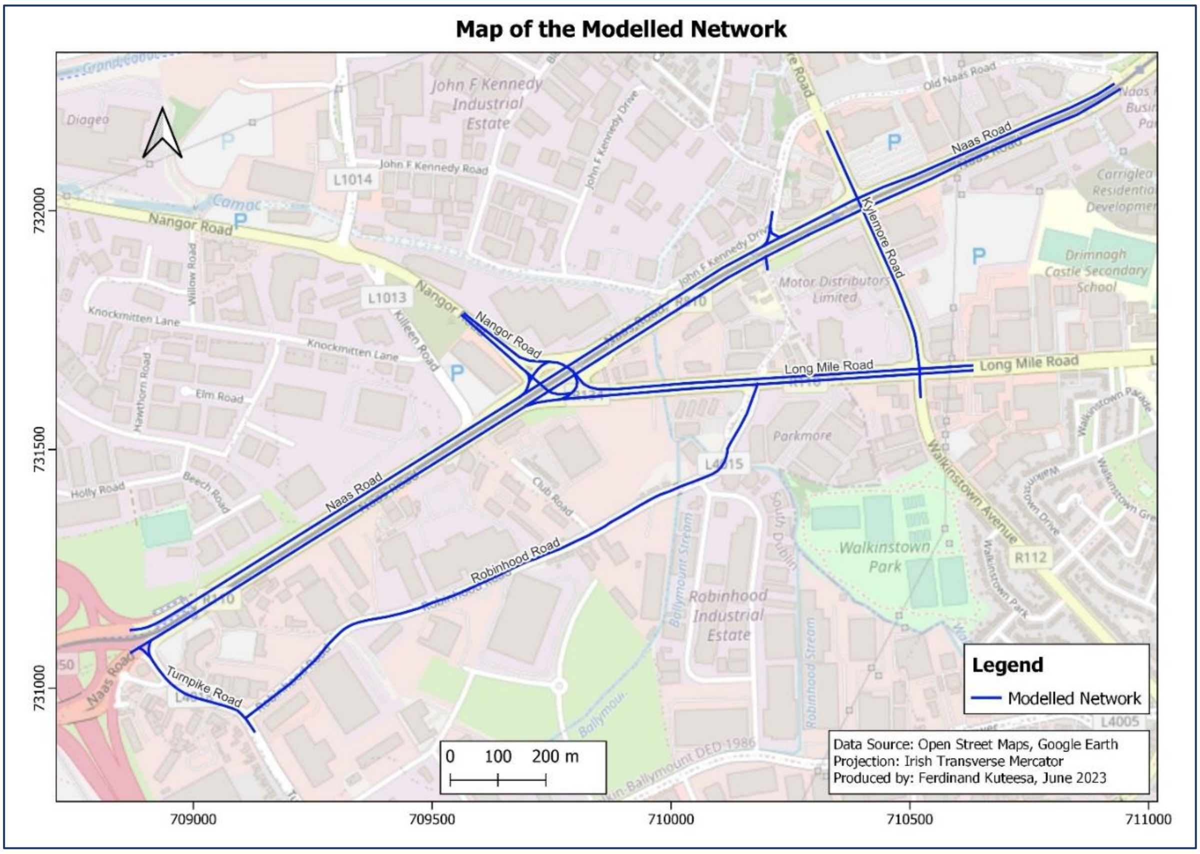

Figure 2. The study network

Data

The traffic data for the study was obtained from the National Transport Model (NTpM), which was accessed through the Terrain-AI project (*19*). The main purpose of the NTpM is to assess and analyse impacts on strategic inter-urban demand, focusing on road, heavy rail, and inter-urban bus transportation along national road corridors (*20*). As such, it only provides traffic data for major links and supplementary traffic volumes for the minor routes within the network were assumed for the purposes of this study. Morning peak traffic volumes along major routes in the network (presented in Table 1) were used to determine the vehicle inputs for the VISSIM model. Notably, the car vehicle category comprised over 96% of the total vehicles while the remaining percentage was attributed to Heavy Goods Vehicles (HGVs).

TABLE 1 Vehicle flow inputs

No.	Road name	Vehicle Inputs (veh/h)		Data Source
		Car	HGV	
1.	Naas Road EB	2779	163	NTpM
2.	Turnpike Road	311	7	Assumed
3.	New Nangor Road	711	27	NTpM
4.	Walkinstown Avenue	737	32	NTpM
5.	Long Mile Road WB	1709	74	NTpM
6.	Naas Road WB	2094	145	NTpM
7.	Kylemore Road	493	15	NTpM
8.	Old Naas Road	112	13	Assumed

VISSIM Base Model

The study's base model with vehicle input points is shown in Figure 3. It included 172 links, with 222 conflict areas. For conflicts, priority was assigned to one of the conflicting movements while in some cases where the conflict was deemed passive, the software was allowed to assign priority during the simulation. Seventy-one signal heads at multiple junctions across the network, 21 routing decisions to assign volumes per movement, and 10 public transport routes with a total of 15 public transport stops were added to reflect real conditions. Junction delay was measured primarily at the junctions shown in Figure 4. The public transport lines incorporated in the model are shown in Figure 5. Bus frequency varies by route and time of day, however, on core routes, buses are expected every 5-15 minutes during rush hour (*21*). By Finally, the model incorporated 51 data collection points and 5 vehicle travel time and delay measurement routes.

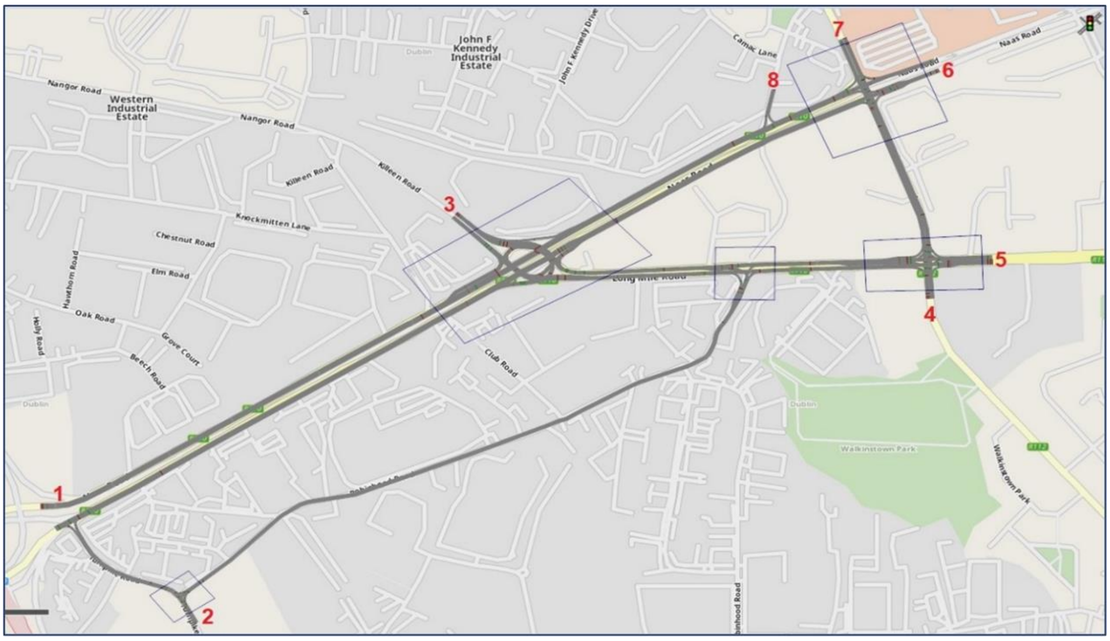

Figure 3 Base model and vehicle input points.

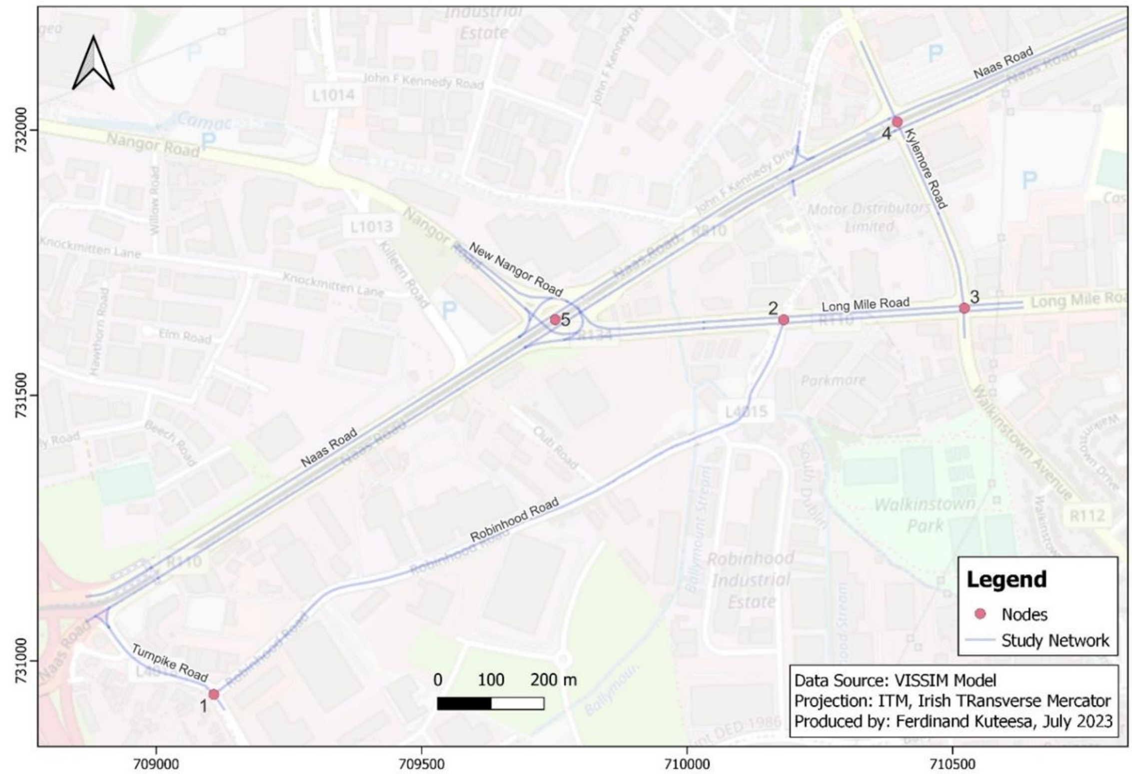

Figure 4. Junction nodes within the model (numbered 1-5)

Public Transport Lines / Line stops

Count: 10	No	Name	EntryLink	DestLink	DestPos	EntTmOffset	VehType	DesSpeedDistr	Color
1	1	Naas Rd EB Route	12: Naas Road/R110	30: Naas Road/R110	196.075	0.0	300: Dublin Bus	30: 30 km/h	(255, 190, 0, 0)
2	2	Naas Rd WB Route	53: Naas Road	48: Naas Road/R110	969.898	0.0	300: Dublin Bus	30: 30 km/h	(255, 0, 168, 0)
3	3	New Nangor-Long Mile Route	32: New Nangor Road	26: Long Mile Road	95.773	0.0	300: Dublin Bus	30: 30 km/h	(255, 224, 224, 0)
4	4	Long Mile-New Nangor Route	25: Long Mile Road	57	50.094	0.0	300: Dublin Bus	30: 30 km/h	(255, 0, 168, 168)
5	5	Walkinstown Av-Kylemore Rou...	19: Walkinstown Aven...	23: Kylemore Road	81.145	0.0	300: Dublin Bus	30: 30 km/h	(255, 168, 0, 168)
6	6	Kylemore-Walkinstown Av Rou...	24: Kylemore Road	65	49.386	0.0	300: Dublin Bus	5: 5 km/h	(255, 0, 0, 0)
7	7	Naas-New Nangor Route	12: Naas Road/R110	57	51.157	0.0	300: Dublin Bus	30: 30 km/h	(255, 127, 255, 212)
8	8	Naas-Walkinstown Av Route	53: Naas Road	65	51.123	0.0	300: Dublin Bus	30: 30 km/h	(255, 138, 43, 226)
9	9	Naas-Long Mile Route	12: Naas Road/R110	26: Long Mile Road	96.690	0.0	300: Dublin Bus	30: 30 km/h	(255, 165, 42, 42)
10	10	Walkinstown Av-Naas Route	25: Long Mile Road	48: Naas Road/R110	971.453	0.0	300: Dublin Bus	30: 30 km/h	(255, 222, 184, 135)

Figure 5. Public transport lines incorporated within the model.

Modelling Behaviours

The human driver model (HDV) model within VISSIM was set to urban motorized, and the driving behaviour, based on the Widemann 74 car-following model, was selected (*16*). Lane change behaviour was set to 'free lane selection', enabling vehicles to change lanes at will. The model also incorporated 'advanced merging' coupled with 'vehicle routing decision look ahead', allowing vehicles to change to their desired lane ahead of a turn, hence simulating a more realistic merging behaviour. Finally, the behaviour at amber signals was set to 'continuous check' implying that vehicles continuously monitor the signal status and adjust their actions accordingly.

The study assumed Level 5 AVs (full automation) as the basic requirement for autonomous vehicles. In level 5 autonomy, the vehicle can perform all driving tasks in any condition or environment without the need for human intervention. For AVs, Sukennik (*22*) describes four driving logics: *rail safe*, *cautious*, *normal*, and *all-knowing*, of which the latter three, by default, are part of VISSIM as separate driving behaviours (*16*). On that basis, in cautious logic, the AV consistently adheres to road traffic regulations and always maintains a safe driving approach. In normal logic, the AV's driving behaviour resembles that of HDVs. In all-knowing logic, the AV possesses complete awareness of the entire traffic situation and utilizes a traffic situation prognosis, enabling it to closely follow other vehicles, resulting in cooperative driving with minimal gaps between vehicles.

It is further recommended that the adoption of different driving logics are applied for different road types with the all-knowing logic normally used for arterials and motorways (*22*). Accordingly, an all-knowing driving logic was adopted for the study since Naas Road, the main road in the network, is an arterial.

Modelled Scenarios

The study modelled seven different scenarios based on various design considerations.

Sc1 – Base Case: The first scenario represents the base scenario with no AVs in the fleet. The lane width was 3.5m, all junctions were signalised, and the speed limit for cars was 50 km/h while for buses and HGVs it was 40 km/h.

Sc2 – 60% AVs in the vehicle fleet: In this scenario, the study examines the effects of introducing AVs into the vehicle fleet, considering a market penetration level of 60%. The road design properties are the same as in Sc1.

Sc3 – Dedicated Lane for AVs: This scenario introduces a lane exclusively dedicated to AVs. The proportion of AVs in the fleet was the same as in Sc2 (60%). As AVs are expected to travel faster than other vehicles, they were assigned the far-right lane on the Naas Road (In Ireland, cars drive on the left) while the middle lane was for all vehicles. The dedicated AV lane was not extended to the intersection and vehicles were allowed to freely select the most convenient lane on approach to the intersection.

Sc4 – 100% AVs: In this scenario, all vehicles are AVs and this scenario enables comparison between an all-HDV fleet (Sc1) and an all-AV fleet. Additionally, this scenario served as a baseline for full autonomous driving, providing a reference point against which the following scenarios involving full automation were compared.

Sc5 – Introduction of a roundabout: In Sc5, a roundabout is introduced at one of the intersections (Long Mile – Robinhood Rd junction – see junction node 2 on Figure 4) in a fully autonomous environment. The objective is to determine whether the design of the roundabout significantly affects the performance of AVs compared to signalized intersections. (Sc1 and Sc5 are presented in Figure 6a and 6b respectively).

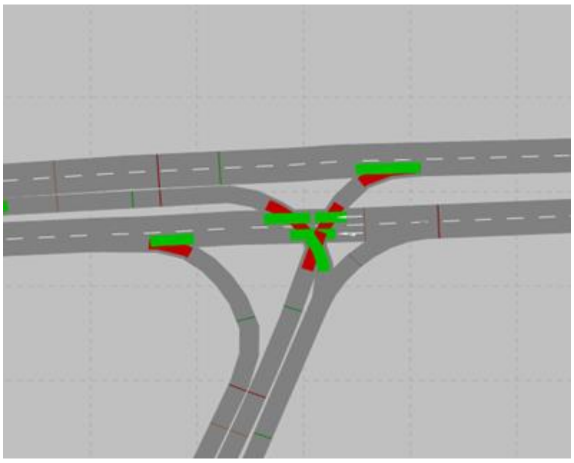

Figure 6a. Scenario 1 (existing signalised)

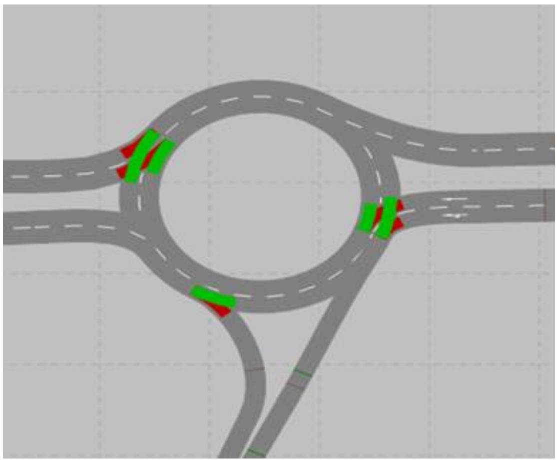

Figure 6b. Scenario 5 (roundabout alternative)

Sc6 – Reduced Lane width: In Sc6, the feasibility and impact of reducing lane width (from 3.5m to 2.5m) in a fully autonomous environment is examined. This scenario is motivated by the expectation that AVs will have increased accuracy and manoeuvring capabilities compared to human drivers, potentially requiring less space on the road.

Sc7 – Increased design speed: This scenario aims to investigate the possibility of safely implementing higher design speeds in a fully autonomous environment.

Simulation and Analysis

The key parameters of focus in the research were volume, speed, travel time, delay and level of service. In addition, a safety assessment based on conflict analysis using surrogate safety measures was conducted for each scenario. For the safety analysis, the study utilized vehicle trajectory data from the VISSIM output file (.trj) and employed the SSAM, which uses advanced algorithms to identify and classify conflicts (*18*). The software utilizes two threshold values as surrogate safety measures to detect and categorize conflicts in vehicle-to-vehicle interactions, applying these thresholds to Time-to-collision (TTC) and Post-encroachment time (PET) values for conflict classification. TTC represents the minimum time-to-collision observed during the conflict, and is based on the current position, speed, and future trajectory of the two vehicles at a specific moment while PET denotes the minimum post-encroachment time observed during the conflict, which is the duration between when the first vehicle last occupied a position and when the second vehicle subsequently arrived at the same position (*18*). The risk classification used in this study are follows:

- TTC and ROC Score of 1: TTC range: 1.6 – 2.0 s, Risk of Collision (ROC) Low.
- TTC and ROC Score of 2: TTC range: 1.0 – 1.5 s, ROC Moderate.
- TTC and ROC Score of 3: TTC range: 0.0 – 0.9 s, ROC High

RESULTS

Throughput Volume

The results presented in Figure 7 represent the total of the throughput volumes observed at different points within the network in vehicles per hour. The throughput volumes at each data collection point were summed to obtain the total throughput volume in the entire network for each scenario and were then compared.

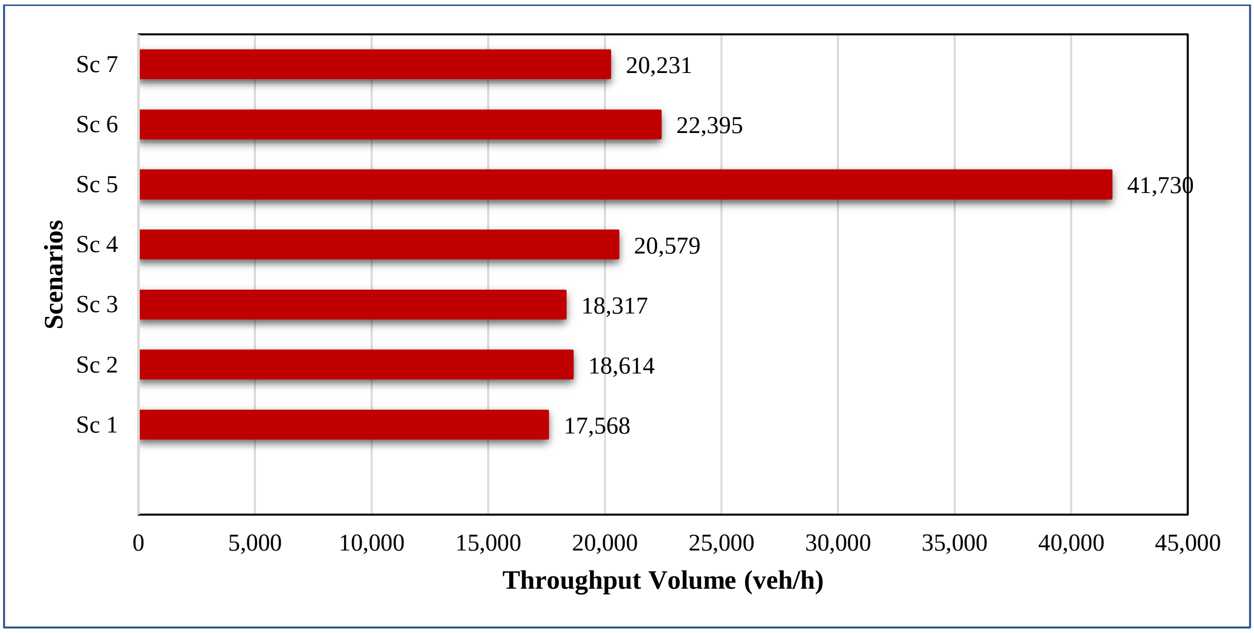

Figure 7 Total throughput volumes in the network per scenario.

As can be seen in Figure 7, implementation of a roundabout design in Sc5 stood out with the highest volume, reaching 41,730 veh/h. This figure was nearly twice as high as the second placed Sc6 (narrower lanes) with 22,395 veh/h and more than two times higher than Sc4 (20,579 veh/h) which was the baseline for a fully AV fleet. In Sc5, both the eastbound (EB) and westbound (WB) directions saw significant increases in throughput volumes when comparing signalised with roundabout design (East: from 398 to 1503 veh/hr; West: from 919 to 1371 veh/hr). This suggests a roundabout design in a fully autonomous fleet allowed for smoother traffic flow and better utilisation of available lanes.

Referring again to Figure 7, Sc3 (dedicated AV lane) had throughput volumes similar to Sc2 with no AV lane. Although on the surface it appears as though the AV lane had no significant impact, a deeper examination revealed notable observations, particularly regarding EB volumes. At a point west of the intersection of the Naas Road-New Nangor Road-Long Mile Road, the EB volume on the Naas Road increased from 971 veh/hr to 1003 veh/hr after implementation of the AV lane. Similarly, at a point east of the intersection, the volume increased from 1148 veh/hr to 1332 veh/hr. In the WB direction, there was no change in volumes. The slight improvement in performance in the EB direction could be attributed to the ability of merging and exiting AVs to quickly navigate through the lanes. It is also worth noting that the WB links did not have any minor intersection between the major intersections to create side merging traffic.

Narrower lanes in Sc6 exhibited the second highest throughput volume. A closer look at the individual volumes revealed that the improvements at three locations, all within the Naas Road-New Nangor Road-Long Mile Road intersection. The largest increase was in the WB traffic (from 2,148 veh/hr to 2,536 veh/hr) but there was also an increase EB from 1,066 veh/hr to 1,352 veh/hr. These results suggest that narrower lanes might have better efficiency for AVs at a complex junction.

Sc2 (60% AVs) recorded a slightly higher throughput volume than that of the base scenario. Meanwhile, Sc4 (100% AVs) recorded an even higher volume. This indicates that, even with a relatively low market penetration of AVs (60%), there is a potential improvement in overall network efficiency, which can be attributed to AVs' faster decision making when compared to HDVs.

Average Speed

The speed of vehicles as they passed each data collection point was averaged. Those speeds were then averaged across the network for each scenario and are presented in Figure 8.

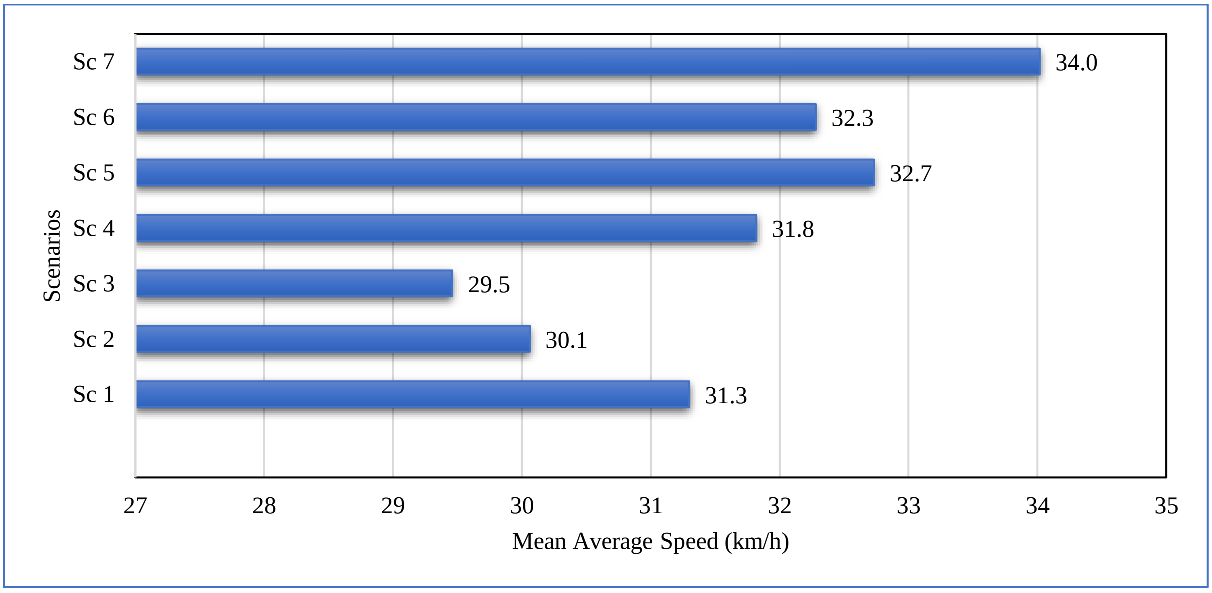

Figure 8 Average speed across network for each scenario.

As illustrated in Figure 8, Sc7 exhibited the highest average speed of 34.0km/h. Sc 4, 5 and 6 also demonstrated relatively higher average speeds of 31.8km/h, 32.7km/h and 32.3km/h respectively than the other scenarios. This implies that, in a fully autonomous environment, both narrower lanes and roundabout designs for intersections could have potential in the context of improving average speeds.

On the other hand, Sc3 (dedicated AV lane) had the lowest mean average speed of 29.5 km/h for the entire network. This slower speed can be attributed to the difficulties associated with merging and yielding at minor intermediate intersections particularly EB on the Naas Road, where HDVs were observed to be more sluggish in merging, turning, and exiting lanes compared to AVs. However, despite recording the lowest overall mean average speed, the WB route on the Naas Road still registered higher average speeds of 43.4 km/h at one point, outperforming all other lanes (23.6 km/h and 29.4 km/h).

This finding underscores the complexities between AVs and non-AVs that can be expected in a mixed fleet environment, but it also suggests that a dedicated AV lane could have even better potential in continuous sections with limited interruptions such as on motorways.

Sc2 (60% AVs) exhibited a mean average speed of 30.1km/h, which was lower than those of Scs 1 (0% AVs) and 4 (100% AVs). This indicates that a mixed fleet of AVs and HDVs could have a negative impact on travel speeds. This was especially noticeable when AVs and HDVs interacted, as AVs seemed to 'bulldoze' the network with their quick decision-making. This was only evident at a 60% AV market penetration level. At full automation in Sc4, the average speed increased.

Total Vehicle Travel Time

In the simulations, the average travel time for vehicles to traverse each of the selected routes was noted. These times were then summed to obtain the total travel time for five selected travel routes through the modelled network. The different total travel times (for all 5 routes) across the 7 scenarios are depicted in Figure 9.

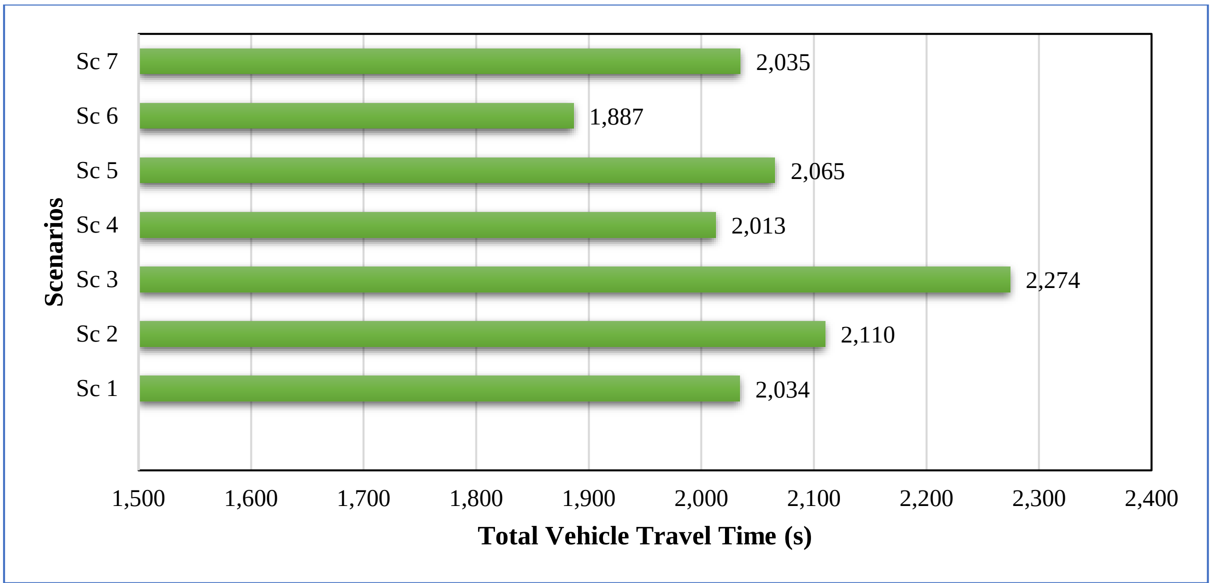

Figure 9. Total vehicle travel time for each scenario.

From the results, Sc3 (dedicated AV lane) had the longest travel time of 2,274s, which was 8% higher than the second placed Sc2 (60% AVs) with a travel time of 2,110s. This could be attributed to additional complexities in merging, yielding, and turning, especially in the EB movement along Naas Road where the presence of access roads and minor junctions caused more challenges for vehicles in the AV lane. In congestion, some AVs intending to make a left turn could not change lanes in time causing them to cross from their lane too close to the turn. This frequently caused other vehicles travelling straight to stop for the crossing AV before proceeding. Although this could happen even without AVs, it was observed that in the presence of AVs, the time it took for HDV traffic to resume movement was longer than in the absence of AVs, most likely because human drivers drive more cautiously when they feel intruded upon, and AVs use a shorter safe distance.

Notably, Scs 2, 5, 7, and 4, had relatively similar travel times. These results suggest that the market penetration level (MPL) of AVs may not have a significant impact on travel time without other additional modifications to the network. Surprisingly, the shortest travel time of 1,887s was observed in Sc6 (narrower lanes). The reduced lane width may have facilitated smoother navigation for AVs.

Delay

Delay was considered from two perspectives a) vehicle delay and b) junction delay, both of which are examined in detail below.

Vehicle Delay

Implementation of a dedicated AV lane in Sc3 exhibited the highest total vehicle delay at 1,664s, (see Figure 10) which was on average 12% higher than Scs 1 (base case), 2 (60% AVs) and 4 (100% AVs). Closer observation revealed that this arose from the failure of HDVs to find merging space as they navigated from the side to find a space in the mixed lane. With AVs dominating the network, it was observed that HDVs exhibited a slower decision-making process, exacerbating the merging issue. However, this challenge was not evident in sections of the network where side merging was not required or during exit manoeuvres.

Conversely, the shortest vehicle delay of 1,347s was exhibited in Sc6 (narrower lanes). The remaining scenarios exhibited similar delays, with higher design speeds (Sc7) having a long vehicle delay of 1,634s while Scs 5, 2, 1, and 4 had values of 1,515s, 1,492s, 1,481s, and 1,480s, respectively. Notably, only Scenario 4 (full autonomy) and Scenario 6 (roundabout design in full autonomy) had a shorter vehicle delay than the base scenario. These findings suggest that the introduction of AV lanes in a mixed fleet may not have the potential to reduce delays.

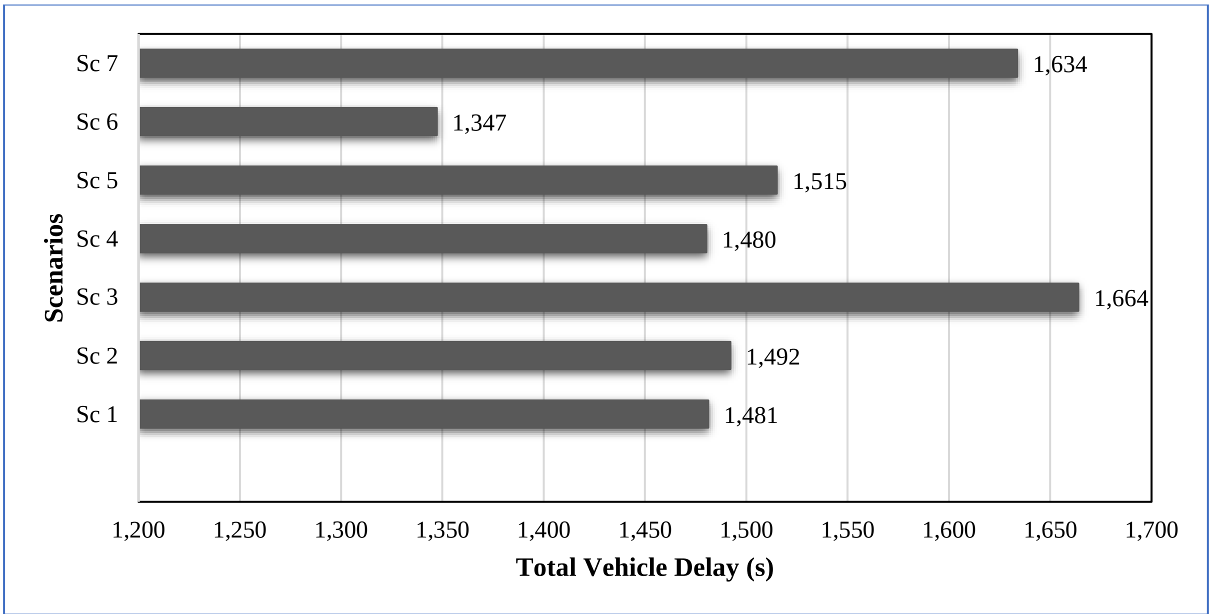

Figure 10. Total vehicle delay for each scenario

Junction Delay

The analysis of junction delays revealed notable differences between scenarios, as shown in Figure 11. Sc3 stood out again with the highest junction delay of 406s. The other scenarios: base case (Sc1), 60% AVs (Sc2), 100% AVs (Sc4), and higher design speed (Sc7) all exhibited significantly lower junction delays of 387s, 369s, 379s, and 392s respectively, but relatively higher than Sc5 (336s) and Sc6 (344s). Notably, only Scs 3 and 7 had higher junction delays than the base scenario.

Figure 12 illustrates the variation in delay in the five junctions across the various scenarios. As shown, the implementation of the AV lane yielded a rise in delay at Junctions 4 and 5, while Junctions 1, 2 and 3 remained relatively unaffected. Notably, Junctions 4 and 5 are situated along the Naas Road, where the AV lanes were implemented, indicating an association between the AV lane and this effect.

The roundabout design in Sc5 exhibited the lowest junction delay of 336s (Figure 11). This is attributed to the improved efficiency of the redesigned intersection (Junction 2), as evidenced by the reduced delay shown in Figure 12. Moreover, Junction 3 also experienced a significant reduction in delay in this scenario which could be attributed to its direct link with Junction 2 in the EB-WB movements.

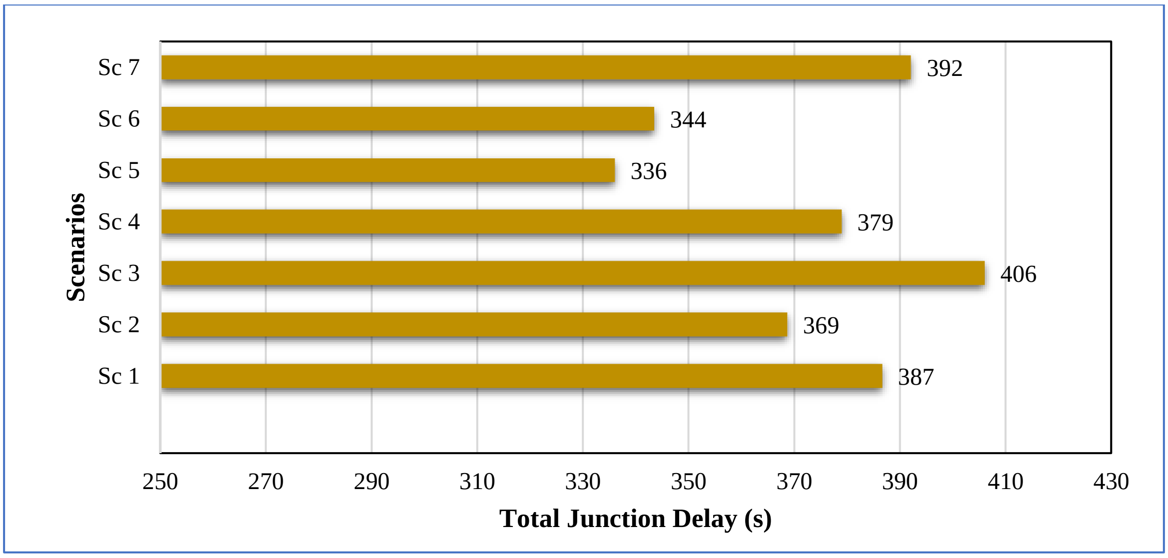

Figure 11 Total junction delay per scenario

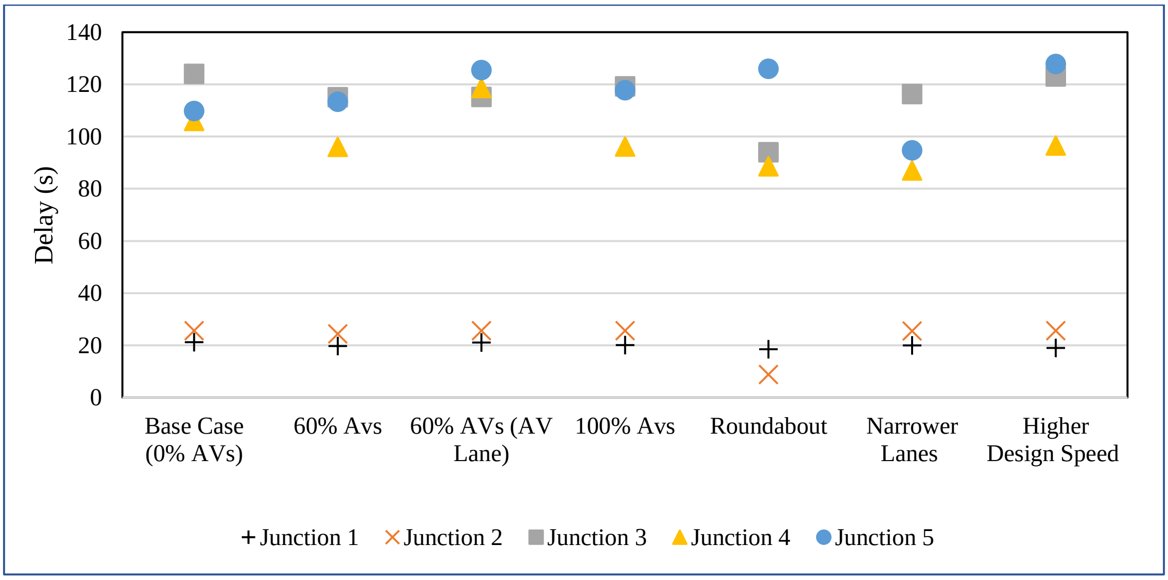

Figure 12 Variation in junction delay at specific junctions on the network.

Sc 6 (narrower lanes) had the second-best junction delay of 344s. Compared to Sc4 which baselined a fully autonomous driving environment, there was no significant improvement in delay in most of the junctions owing to these geometric modifications. Only Junction 5 registered a significant improvement from 118s to 95s. This positive outcome can be attributed to the optimized utilization of available space within this complex junction, thereby facilitating smoother vehicle manoeuvres.

Queue Length

The queue length results presented in Figure 13 illustrate the average maximum queue length at intersections within the network per scenario. The results indicate that Sc3 (dedicated AV lane) had the highest average queue length of 307m. Sc1, the base scenario, and Sc7 (higher design speed) followed closely with values of 300m and 299m respectively. Sc4 and Sc6 exhibited similar average queue lengths of 296m and 294m, respectively. Sc2 with mixed AV and HDV traffic performed better with an average queue length of 288m while the roundabout design in Sc5 exhibited the shortest queue length of 250m.

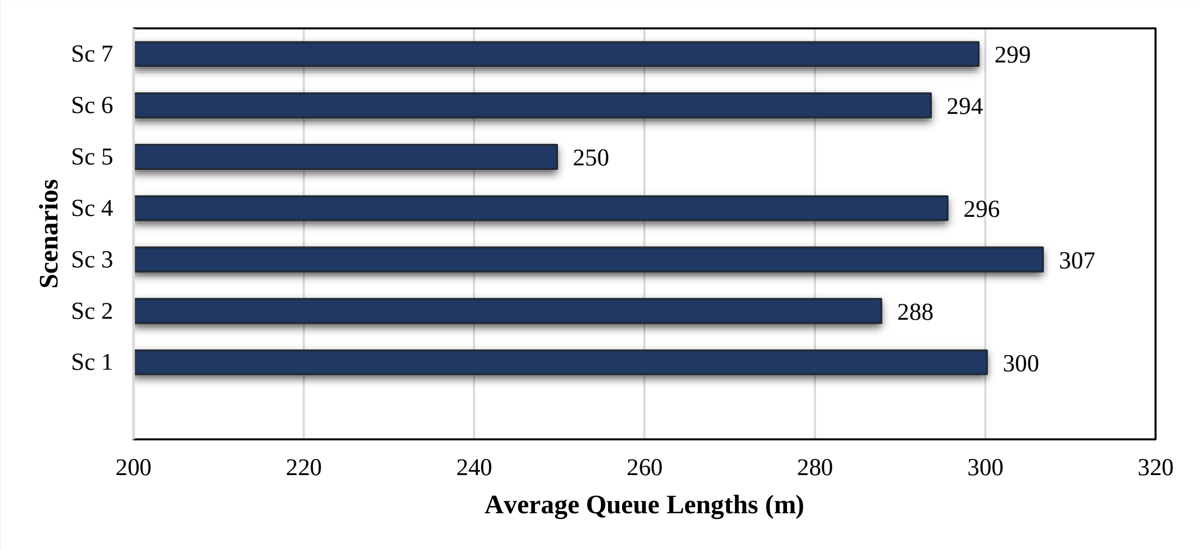

Figure 13 Average queue lengths per scenario

Level of Service

In VISSIM, as well as the Highway Capacity Manual, the level of service (LOS) for a node or intersection is evaluated using a scale ranging from 1 to 6. LOS A, which represents the best level of service is represented by a value of 1, while LOS F, indicating the worst level of service is represented by a value of 6 (*16, 24*). The LOS results are shown in Figure 14.

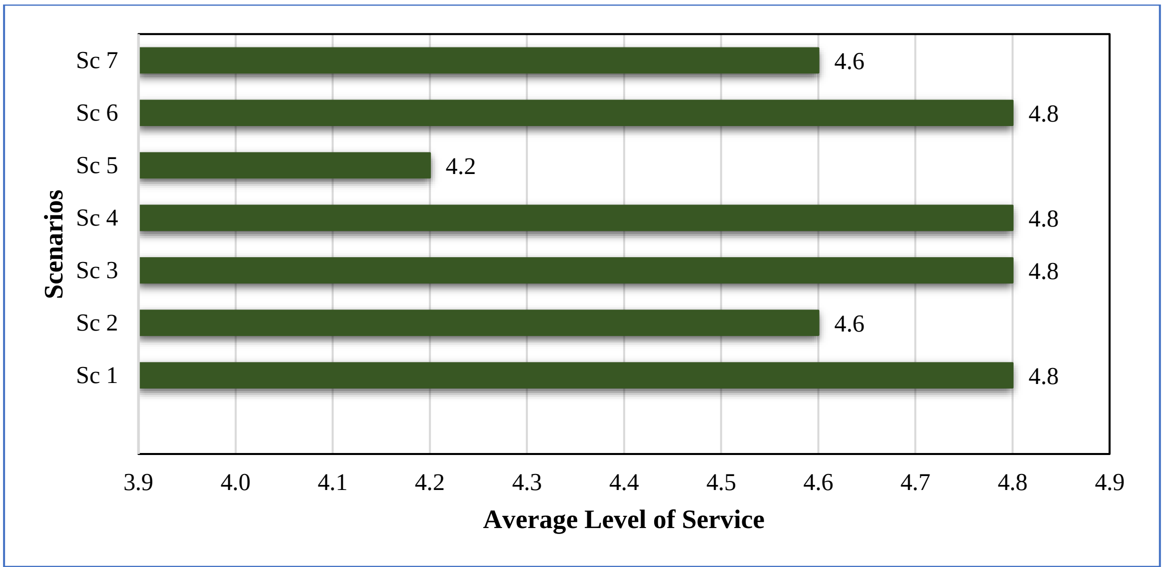

Figure 14 Average travel service per scenario

The study noted variations among the scenarios with the base case (Sc1), the dedicated AV lane (Sc3), 100% AVs (Sc4), and narrower lanes (Sc6) all exhibiting the same average LOS value of 4.8, indicating relatively poor traffic conditions. Sc2 (60% AVs) and Sc7 (higher design speeds, 100% AVs) exhibited a slightly better LOS value of 4.6. Sc5 (roundabout design) recorded the best average LOS value of 4.2.

Safety Analysis

Conflict Categories

For each scenario, the conflicts were categorized into three types: rear-end, lane change, and crossing and this is presented in Figure 15. (Note the numbers for crossing conflicts are considerably smaller than the other categories and so are difficult to discern on the figure). The implementation of narrower lanes in Sc6 resulted in the highest number of conflicts (38,091), indicating a significant level of interaction and potential collision occurrences within this setting.

It is noteworthy that all scenarios involving full automation (Sc4 – 7), irrespective of the geometric modifications, had a significant number of conflicts, with Sc4 (100% AVs) recording the second highest at 35,718 conflicts, Sc7 (increased design speed) registering 34,936 conflicts and Sc5 (roundabout design) coming in closely at 32,806 conflicts. This highlights the inherent safety challenges associated with automated driving and underscores the critical necessity for implementing measures aimed at addressing and mitigating conflicts.

It is also worth noting that among the aforementioned four scenarios, the roundabout design exhibited the lowest rear-end conflicts, even surpassing Sc4, the benchmark for full automation. This outcome aligns with the established understanding that roundabouts reduce exposure to rear-end conflicts in a traditional vehicle environment (*25*).

The base case scenario (Sc1) recorded the lowest number, with a total of 6,906 conflicts followed by Sc2 (60% AVs) and Sc3 (60% AVs +AV lane) with 16,842 and 25,581 conflicts respectively. This performance can be attributed to the less aggressive driving behaviour of HDVs in these scenarios compared with the AVs.

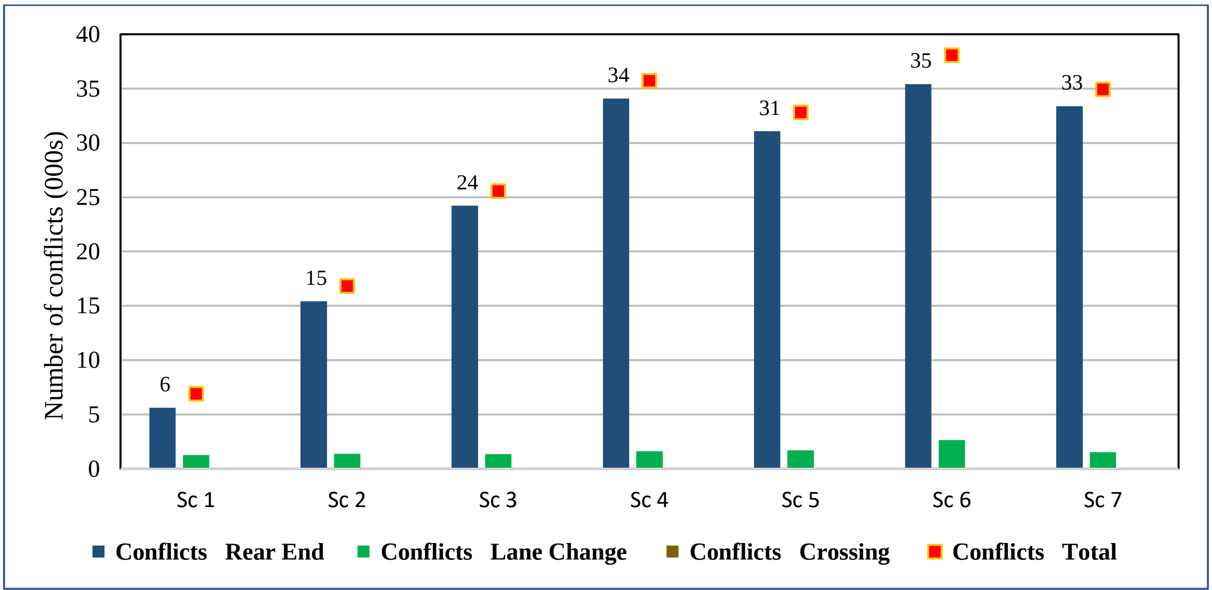

Figure 15. Variation in conflict categories for each scenario.

Conflict Severity

The severity of conflicts was further classified into three levels: high-risk (HR), moderate-risk (MR), and low-risk (LR) based on the time to collision (TTC). Figure 16 illustrates the variation of severity across the different scenarios. Notably, there were no low-risk conflicts recorded.

From Figure 16, it can be seen that there is generally an upward trend, across both severity levels, when moving from Sc1 to Sc7. Notably, the introduction of AVs into the vehicle fleet in Sc2 resulted in an increase in conflicts, with the moderate risk conflicts rising more sharply than high-risk. This surge in conflicts may be attributed to the comparatively more aggressive driving behaviour exhibited by AVs, leading to situations where they overtake, merge, and prompt HDVs to yield, thereby influencing conflict dynamics.

Similarly, a dedicated AV lane (Sc3) yielded another increase in conflict occurrences. This could be attributed to the AV lane's elevated travel speeds along its stretch which could also be a catalyst for increased conflicts. This comes as no surprise, as the severity of conflicts observed in Sc7 was even higher due to the increased travel speeds. The correlation between higher speeds and intensified conflicts could also be explained by the need for longer SSDs and decision sight distances (DSDs) that are crucial for safe vehicle interactions.

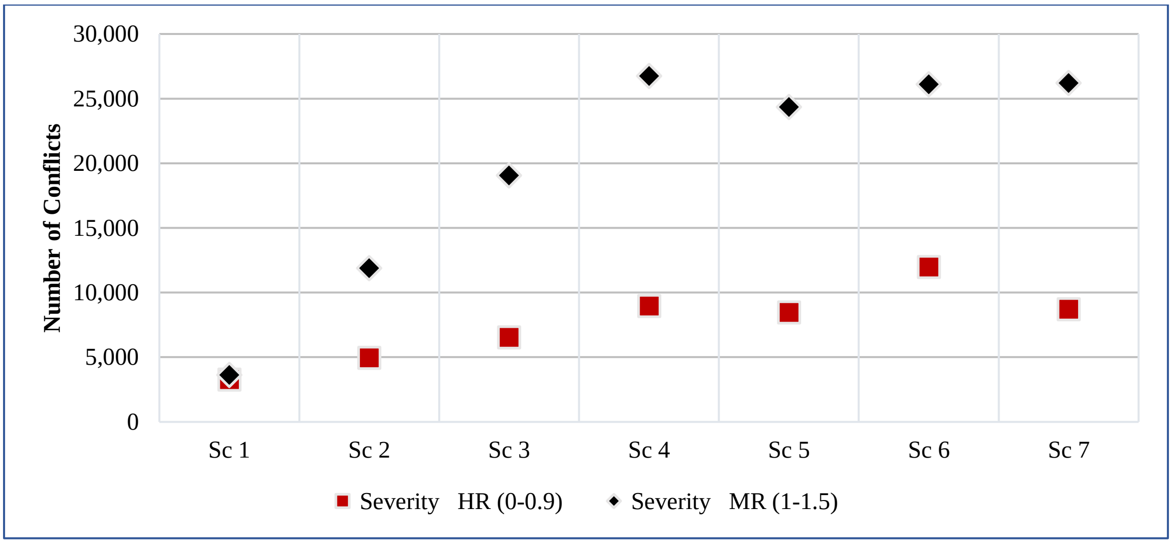

Figure 16 Categorisation of conflicts based on severity

Figure 17 presents the distribution of conflicts in Sc3, based on their severity. Conflicts with TTC ≤ 0.5s are depicted in red, those with TTC ≤ 1.0s are in yellow, and conflicts with TTC ≤ 1.5s are designated in blue. Evidently, the majority of the high-risk conflicts occurred at intersections, while the moderate conflicts occurred primarily along road links with the Naas Road-New Nangor-Long Mile Road Junction showing the highest concentration.

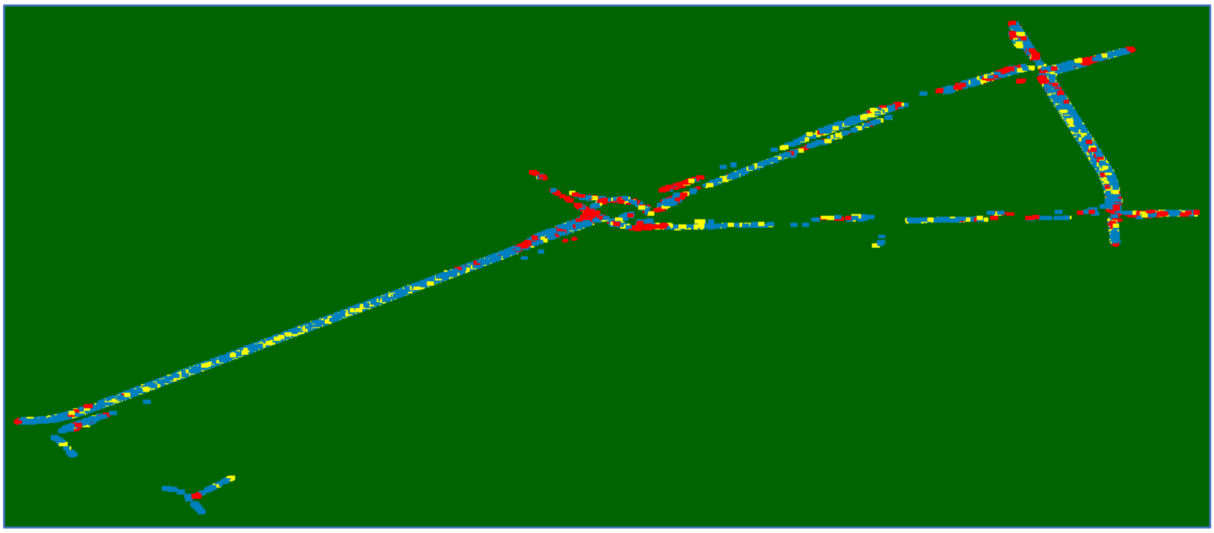

Figure 17 Location of different conflict types.

A marginal reduction in conflicts was observed in Sc5 (Figure 16), where a signalized intersection was replaced by a roundabout. This geometric modification seemed to have a moderating effect on both types of conflicts, leading to a slight decrease in their overall numbers. This outcome aligns with other findings (*25*), which demonstrated that roundabouts were associated with decreased exposure to rear-end conflicts as compared to signalized junctions. Although their conclusions were derived in a traditional vehicle environment, the results of this study suggest that the same can be expected in a fully autonomous environment.

In Sc6, where lanes were narrowed to 2.5m, conflict occurrences resurged, adhering to the overarching pattern of escalating conflict levels observed in prior scenarios. Sc7 (higher design speed) was the only scenario to record a conflicting trend between the two conflict categories, registering a significant reduction in high-risk conflicts while simultaneously experiencing a slight elevation in moderate-risk conflicts when compared to Sc6.

DISCUSSION

This research aimed to explore the potential impact of AVs on the geometric design of highways. Introducing a 60% MPL of AVs in Sc2 initially showed positive signs of improved throughput and reduced queues, however, this was counterbalanced by a drop in average speed, longer travel times and notable traffic conflicts. These outcomes underscore the intricate dynamics between AVs and HDVs, emphasizing the necessity of a comprehensive approach when evaluating their effects on traffic flow and highway design.

Contrary to expectations, the dedicated AV lane exhibited the lowest throughput volumes, slowest mean average speed, longest travel times, and highest vehicle and junction delays. Additionally, traffic conflicts substantially increased, nearly doubling. This finding aligns with that of other research (*26*) which demonstrated that the implementation of an AV lane did not yield significant improvements in average commute time, but rather resulted in a 25% reduction in travel time for AVs at the expense of a 7% increase in delay for HDVs. These findings highlight the complexity of introducing a dedicated AV lane in a mixed traffic environment, emphasising the necessity for meticulous evaluation to ascertain its viability and effectiveness.

The introduction of a fully autonomous environment, as expected, yielded a considerable improvement in traffic performance. Throughput volumes, average travel speed, travel time, and vehicle and junction delays all showed significant improvements, while queue lengths were notably reduced. However, despite these positive outcomes, there were noteworthy concerns in this scenario: the LOS remained poor, indicating that, even with full automation, the network's efficiency and performance might still fall short of desired standards. Moreover, the substantial increase in traffic conflicts, surpassing the values of the base scenario by more than double, was noted.

The introduction of a roundabout design in a fully autonomous environment, as an alternative to a signalized junction, demonstrated remarkable improvement. However, it is worth noting that the total network vehicle delays and travel times remained poor in this scenario which could be attributed to the fact that the performance of a single intersection might have a limited impact on the overall network's efficiency and travel times. Nevertheless, the results suggest that the adoption of a roundabout design holds great potential to enhance traffic conditions in a fully autonomous environment.

The study explored the use of narrower lanes based on the premise that an AV's precision requires less roadway space for manoeuvring compared to an HDV. The results revealed notable improvements in travel time and vehicle delay, suggesting that the narrower lanes contributed to smoother traffic flow and reduced delays likely due to easier manoeuvrability, especially in the complex junctions. Additionally, the average speed performance was still satisfactory but not improved, indicating that the narrower lanes did not significantly impact on travel speeds.

Increasing the design speed yielded results that fell short of the initial expectations. While average travel speed within the network exhibited robust performance, the overall impact on other parameters was average at best. The scenario demonstrated a high number of conflicts but, on a more positive note, the LOS was better than for the majority of the scenarios, trailing only behind the roundabout design.

Strengths and Limitations

This study presents an exploration of the intricate relationship between AVs and highway design. A notable strength lies in its quantitative methodology, which employs in-depth data analysis to objectively assess the performance of different scenarios.

In terms of weaknesses, while the study examined a wide range of scenarios, these modifications are not mutually exclusive, and their interactions could lead to nuanced outcomes that could not be fully captured by the independent analysis of each scenario. The study also explores one specific type of AV driving behaviour i.e., all-knowing, which may limit the transferability of its findings to other driving behaviours exhibited by AVs. The study's simulation-based approach and reliance on assumptions for some vehicle inputs and route decisions should also be noted. Furthermore, the study did not account for pedestrians and cyclists.

Future Policy Implications

Based on the findings of the study, several policy proposals can be deduced to guide the integration of AVs into highway geometric design and traffic management:

1) *Holistic Evaluation:* Prioritize thorough assessments of AV impacts on highway design, encompassing factors like safety and network efficiency, to inform design changes effectively.
2) *Phased Introduction of AVs:* Advocate for a gradual transition to AVs, allowing time for understanding AV-HDV interactions and fine-tuning design strategies.
3) *Cautious Implementation of Dedicated AV Lanes:* Exercise caution with dedicated AV lanes, ensuring careful evaluation of their impact on traffic performance, delays and overall network efficiency.
4) *Consider Roundabout Designs:* Consider roundabout designs in high AV penetration areas to enhance traffic flow and safety.
5) *Balancing Lane Width Reduction:* Approach reduction of lane width cautiously, prioritizing safety and contextual AV-HDV dynamics.
6) *Optimizing Design Speeds:* Strive for balanced design speed increases while considering safety impacts.
7) *Public Awareness and Education:* Launch public education campaigns to promote safer AV interactions and inform drivers about AV capabilities and limitations.

CONCLUSIONS

The research provides valuable insights into the potential impact of AVs on the design of highways. While certain design modifications showed promising improvements in specific parameters, caution is warranted in implementing design changes as potential challenges in interactions between AVs and HDVs were highlighted.

The conclusions are as follows:

1) A dedicated AV lane shows mixed results, with improvements in some parameters and a negative impact on the overall network performance.
2) A fully autonomous fleet demonstrates enhanced throughput volumes and junction performance, however, safety concerns and conflicts must be carefully considered and studied further.
3) The roundabout design emerges as a promising solution for AV integration, showcasing remarkable improvements in various indicators.
4) Narrower lanes have the potential to improve travel time and reduce vehicle delay in a fully autonomous environment but raise safety concerns due to increased lane change conflicts.

AUTHOR CONTRIBUTION

The authors confirm contribution to the paper as follows: study conception and design: F.T. Kuteesa, M. O'Mahony; data collection: F.T. Kuteesa; analysis and interpretation of results: F.T. Kuteesa, M. O'Mahony; draft manuscript preparation: F.T. Kuteesa, M. O'Mahony. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Singh, S. K. Road Traffic Accidents in India: Issues and Challenges. *Transportation Research Procedia*, 2017. 25**,** 4708-4719.

2. Wang, X., D. Qin, S. Cafiso, K.K. Liang, K. K. and X Zhu. Operational Design Domain of Autonomous Vehicles at Skewed Intersection. *Accident Analysis & Prevention,* 2021. 159**,** 106241.

3. Iravani, H., A. Anderson, and A. Bevan, A. Autonomous Vehicles: Rethinking Traffic Congestion Solutions in Cities. *Journal of Geotechnical and Transportation Engineering,* 2018. 4, 1, 25-29.

4. AASHTO. Policy on Geometric Design of Highways and Streets. *American Association of State Highway and Transportation Officials*, 2018, *Washington, DC*.

5. Khoury, J., K. Amine, and R. Abi Saad. An Initial Investigation of the Effects of a Fully Automated Vehicle Fleet on Geometric Design. *Journal of Advanced Transportation,* 2019**,** 6126408.

6. Ye, X., X. Wang, S. Liu, and A. P. Tarko. Feasibility Study of Highway Alignment Design Controls for Autonomous Vehicles. *Accident Analysis & Prevention,* 2021. 159**,** 106252.

7. Wang, S., B., Y. Ma, J. Liu, and W. Zhou. Impacts of Different Driving Automation Levels on Highway Geometric Design from the Perspective of Trucks. *Journal of Advanced Transportation*, 2021**,** 5541878.

8. Intini, P., P. Colonna, N. Berloco, and V. Ranieri. Rethinking the main road design concepts for future Automated Vehicles Native Roads. *European Transport*, 2019. 73**,** 1-28.

9. Tafidis, P., H. Farah, T. Brijs, and A. Pirdavani, "Everything Somewhere" or "Something Everywhere": Examining the Implications of Automated Vehicles' Deployment Strategies. *Sustainability,* 2021, 13**,** 9750.

10. Algomaiah, M. and Z. Li. Next-Generation Interchange Control Based on Centralized Management of Connected and Autonomous Vehicles. 2019. *IEEE Access,* 7**,** 82939-82955.

11. Zhao, Y., X. Ying, and J. Li. Research on Geometric Design Standards for Freeways under a Fully Autonomous Driving Environment. *Applied Sciences,* 2022. 12**,** 7109.

12. Lyon, B., N. Hudson, M. Twycross, D. Finn, S. Porter, Z. Maklary, and S. T. Waller. Automated Vehicles: Do We Know Which Road to Take? Infrastructure Partnerships Australia, Sydney, Australia, 2017. https://apo.org.au/sites/default/files/resource-files/2017-09/apo-nid112591.pdf Accessed July 2, 2024.

13. Somers, A., and K. Weeratunga. Automated Vehicles: Are We Ready? Internal Report on Potential Implications for Main Roads, Main Roads Western Australia, Perth, Australia, 2015.

14. Hamilton, B. A., and New Jersey Institute of Technology. Dedicating Lanes for Priority or Exclusive Use by Connected and Automated Vehicles. National Cooperative Highway Research Program, Transportation Research Board, Washington D.C., 2018.

15. Hossain, M.M., M R.A Lima and H. Zhou. Potential Impacts of Connected and Autonomous Vehicles on Controlling Criteria for Road Geometric Design: A Review. *Transportation Research Record*. 2024, 1-12.

16. PTV. VISSIM Modelling Software. https://www.ptvgroup.com/en/products/ptv-vissim Accessed July 2, 2024.

17. Federal Highway Administration. *Surrogate Safety Assessment Model Overview*. https://highways.dot.gov/research/safety/ssam/surrogate-safety-assessment-model-overview Accessed July 2, 2024.

18. Federal Highway Administration. Surrogate Safety Assessment Model and Validation: Final Report. 2008.

19. National Centre for Geocomputation. Terrain-AI Uncovering new insights to suppot ffective climate change decision making. 2021. https://terrainai.com/ Accessed June 20, 2024.

20. Transport Infrastructure Ireland. National Transport Model Update *Variable Demand Model Report.* 2021. https://www.tii.ie/media/h0odc1do/ntpm-vol4-variable-demand-model-report.pdf Accessed July 2, 2024.

21. Dublin Public Transport. *Dublin Buses* https://www.dublinpublictransport.ie/dublin-buses 2018. Accessed July 2, 2024.

22.Sukennik, P. 2020. Micro-Simulation Guide for Automated Vehicles—Final. https://www.rupprecht-consult.eu/fileadmin/user_upload/D2.5-Micro-simulation-guide-for-automated-vehicles.pdf Accessed July, 2, 2024.

23. Sayed, T. and S. ZEIN, S. Traffic Conflict Standards for Intersections. *Transportation Planning and Technology*, 1999. 22, 309-323.

24. Transportation Research Board. *Highway Capacity Manual* Transportation Research Board (TRB). 2016.

25. Saccomanno, F. F., F. Cunto, G. Guido, and A. Vitale. Comparing Safety at Signalized Intersections and Roundabouts Using Simulated Rear-End Conflicts. *Transportation Research Record,* 2008, 2078**,** 90-95.

26. Ivanchev, J., A. Knoll, D. Zehe, S. Nair, S. and D. Eckhoff, D. Potentials and implications of dedicated highway lanes for autonomous vehicles. *arXiv:1709.07658*. 2017.