Proceedings of the 10th World Congress on New Technologies (NewTech'24)
Barcelona, Spain - August 25-27, 2024
Paper No. ICCEIA 153
DOI: 10.11159/icceia24.153

Assessing the Impacts of Autonomous Vehicles for Freeway Safety

Hisham Y. Makahleh[1,2], Haitham A. Badrawi[2], Akmal Abdelfatah[2]
[1]Department of Civil Engineering, School of Engineering, University of Birmingham
Birmingham B15 2TT, UK
First.b00064747@aus.edu; Second.b00071717@alumni.aus.edu
[2]Department of Civil Engineering, Faculty of Engineering, American University of Sharjah
PO BOX 26666, Sharjah, UAE
Third.akmal@aus.edu

Abstract **-** Autonomous vehicles (AVs) are being deployed as one of the vital elements for the future of transportation services. Automated vehicle technology is developing rapidly, and this prompted researchers to further assess their impacts on transportation networks. One of the most critical situations when deploying AVs is the mixed traffic conditions. This situation will be faced when the deployment is not full (i.e., the percentage of AVs in the traffic flow (market share) is not 100% yet). Therefore, there will be an interaction between AVs and regular vehicles (RVs). This research aims to evaluate the implications of AVs on freeway traffic safety. This investigation considered the section of the road of E311 (Sheikh Mohamed Bin Zayed Road) freeway in Dubai, UAE as the test corridor for the study. Microsimulation software (PTV VISSIM) is used to simulate and assess different traffic scenarios. The developed model aimed to forecast potential traffic accidents on the freeway. In this experiment, a total of 7 demand-to-capacity (D/C) ratios and 10 market share values are considered. The findings indicate that the integration of AVs significantly reduces the frequency of potential traffic accidents. Notably, the largest reductions in accident rates, ranging from 70% to 100%, occur when AVs comprise between 40% to 100% of the traffic. Moreover, the results suggest that complete elimination of potential traffic accidents is achievable with full AV deployment, thereby removing human-driven vehicles from the freeway. This research underscores the substantial safety benefits that AVs could deliver as their presence in traffic flows increases, highlighting their crucial role in enhancing freeway safety.

Keywords**:** Autonomous vehicles, regular vehicles, traffic safety, freeway safety, road traffic accidents (RTAs).

1. Introduction

The dependence on automobiles has been rapidly increasing in recent decades and thus resulting in further pressure on the transport infrastructure systems. The immense pressure on the transportation infrastructure could potentially lead to additional traffic congestion [1]. Consequently, the continuous increase in traffic congestion is causing economic losses, delay, drivers' discomfort and most importantly road traffic accidents (RTAs) [1]. Several solutions have been proposed to mitigate RTAs such as costly upgrades of the transportation infrastructure, improving the skills of drivers, and the use of technologies that reduces human involvement [2, 3]. Autonomous vehicles (AVs) are vehicles that can navigate with reduced to no human input [1]. This is unlike regular vehicles (RVs) where human interaction is always required. AVs operate using devices that are capable of understanding and sensing the surrounding environment [1]. While human error accounts for more than 90% of RTAs, AVs could potentially improve traffic conditions, reduce deaths and road injuries [4, 5]. According to the US National Highway Traffic Safety Administration (NHTSA), the vehicle automation is defined as six levels, ranging from 0 to 5 [6]. First, level 0 represents zero automation capabilities. In other words, the driver is responsible for performing all driving tasks. Level 1 involves driver assistance, where the vehicle is controlled by the driver while having limited driving assistance features like cruise control, and lane keeping. Level 2 refers to partial automation, where the driver has access to features that control acceleration, braking and steering. Level 3 includes conditional automation, where the vehicle can perform all aspects of the driving task under some circumstances and the driver must always be ready to take control of the vehicle. Level 4 refers to a high automation level, where the vehicle can perform all driving functions with the presence of a driver that may take control of the vehicle at any time. Level 5 is full automation, which involves AVs capable of performing all driving functions under all environmental conditions while eliminating the human factor. The AVs, which are estimated to have a market share of up to 80% by 2045, have various benefits and are equipped with various technologies that can assist the driver [7]. Research suggests that AVs can improve safety of roadway users by eliminating human error. In addition, using AVs enables commuters to have a more pleasing experience. This is by allowing the AV users to spend the travel time doing work or in pursuing other activities in their vehicles. In addition, the automated vehicle technology can promote mobility independence for the young, the elderly and the disabled [8]. In addition to safety, travel time can be reduced as AVs require less space headways and take the fastest paths to destinations [9]. Despite the promising future and benefits AVs promote, there are still barriers to their implementation. First, the technologies that AVs require, like sensors, increase the cost of AVs and might make them less affordable to several individuals [10]. In addition, the transition period, which will likely involve AVs along with regular vehicles together on streets, needs to be studied to ensure safety of users since AVs accidents are mainly due to other users like drivers, cyclists, and pedestrians [11].

2. Literature Review

The following sections summarize the previous research conducted to assess the impacts of AVs and the automated vehicles' technology on traffic management, performance and safety. A handful number of studies reported that AVs mitigate traffic congestion and reduce RTAs. These reductions would become greater as the AV penetration level increased [2, 3, 12, 13, 14]. Weijermars et al. [15] conducted a study to forecast road safety impacts of AVs using various so-called-sub-use cases (SUCs) interventions. These interventions are related to urban transport, passenger vehicles and freight transport that can be implemented by policy makers. The SUCs are estimated by comparing the situation with intervention with the situation without intervention (baseline scenario). According to Weijermars et al. [15] and Tafidis et al. [16], AVs are expected to have less crash rate, lower reaction time, and decreased variability in driving behaviours compared to human drivers. Similarly, Morando et al. [17] noted that as AVs market share rates increase, road safety drastically improves. Moreover, at intersections, AVs market share levels between 50% and 100% reduces the overall conflicts by 20% to 65% [17]. Tan and Zhang [18] developed a computational cognitive model to predict driver response times during scheduled freeway exiting takeovers, highlighting the importance of driver training and simulation. By the same token, Kerimov et al. [19] stated that using automated vehicle technology increase traffic safety dramatically. Maher et al. [20] applied Bayesian hierarchical models for real-time crash prediction, offering innovative approaches to autonomous driving. Deng et al. [21] proposed a deep reinforcement learning decision-making framework for AVs that integrates risk assessment. They utilized a long short-term memory model to predict surrounding vehicle trajectories and estimate future risks. Their framework outperformed rule-based methods in traffic efficiency and vehicle safety under high-density traffic scenarios. Likewise, AVs enhance intersection and road capabilities significantly as they are designed to travel with shorter headways while maintaining the safety of the roads [22]. Mohammed and Aprad [23] performed a macrosimulation traffic study to estimate the impacts of AVs on four parameters: travelled daily kilometres and daily hours, total daily delay and average network speed. Their analysis shows an improvement across all four parameters by implementing AVs with total delay having the most significant reduction. Fujiu et al. [24] investigated the traffic flow impacts of AVs in rural and urban regions using a traffic flow simulator. Their results indicated that with increasing AV penetration rates, traffic delays initially increased, but then stabilized and gradually decreased. This highlights the importance of considering AV mixing rates when planning their societal implementation. Elsammadisy et al. [25] suggested reinforcement learning-based car-following models, demonstrating that AVs with adaptive algorithms outperform traditional rule-based systems in complex traffic. AVs have the potential to improve road safety as they eliminate major traffic crashes related to human errors, drugs and alcohol [26, 27, 28]. It is also noted that AVs could provide overall enhanced mobility for the disabled and younger drivers as well as the elderly ones [29]. AVs are also of prime importance to lower emissions, reduce parking costs, enhance fuel efficiency, extend productive use of travel time [30, 31]. Moreover, AVs tend to mitigate traffic congestion as they are connected [32]. Makahleh et al. [33] conducted a systematic review to assess the role of autonomous vehicles in urban environments. The findings reveal that AVs have the potential to greatly increase traffic efficiency, safety, and climate resilience in urban contexts. They emphasized how AVs could result in significant drops in greenhouse gas emissions. However, their study also alluded to the urgent need for updated legislation and regulatory frameworks to accommodate these emerging technologies effectively. This entails modifying the infrastructure, enacting laws to protect users, and creating comprehensive frameworks to promote sustainable living. Dresner and Stone [34] developed a reservation-based system for mitigating traffic congestion, precisely for connected vehicles at intersections. The outcomes reveal that the proposed mitigation traffic congestion system for connected vehicles out-performs traffic light policy. Hence, successfully handling much heavier traffic volumes. Furthermore, Dresner and Stone [35] indicated that as the number AVs on the road increase, traffic delays decrease. Several studies reported the impacts of AVs on pedestrians and public health awareness [36, 37, 38, 39, 40, 41, 42, 43, 44]. Tafidis and Pirdavani [45] presented a comprehensive review of surrogate safety measures (SSMs) for AV simulation, emphasizing the need for more accurate thresholds that capture AV-specific behaviours. Utriainen [46] investigated the potential impacts of AVs on pedestrian safety by investigating 40 fatal crashes between pedestrian and driver-managed cars that are replaced by AVs. The results showed that in full automation scenario, 73% of the crashes could have been avoided. Similarly, Saranti and Chondrogianni [47] designed a survey of 160 participants to study the impacts of AVs on pedestrian safety. AV technologies reduce car ownership and encourage car-sharing and pooling schemes. As a result, mitigating traffic congestion, lowering emissions, and reducing direct and indirect costs. Stoiber et al. [48] designed an experiment with 709 participants to explore user preferences for shared and pooled-use AVS. The study assumed full-market penetration of AVs. The results show that AVs are likely to be used in pool mode. The survey results indicated that 61% of participants preferred using pooled AVs over privately owning one. Shatanawi and Mészáros [49] deployed a simulation based dynamic traffic assignment using VISSIM to test the impacts of various AVs and Shared Autonomous Vehicles (SAVs) penetration ratios on Budapest's network performance. Their results reveal that the emergence of AVs and SAVs would improve the overall network performance when increasing the penetration of SAVs. Pakzadnia and Hassan [50] examined freeway merging strategies, finding that cooperative AV merging can reduce crashes. Jung et al. [51] used a multi-agent driving-simulation (MADS) approach to reveal that road curves and slopes increase conflict rates between AVs and RVs. Silva et al. [52] carried out a systematic review of the scientific literature of the environmental impacts of AVs related to noise, water, land, as well as light and air pollution. The results show that when considering mixed scenarios with RVs and AVs, pollution decreases as the percentage of AVs in traffic flow increases. Furthermore, AV technologies could provide better access to safer, cheaper, cleaner, and more efficient mobility [53]. In contrast, Tibljas et al. [54] reported an increase in the estimated crash number at roundabouts when AVs penetration ratios increased. Furthermore, vehicular AVs failure contributes to higher accident rates and might substitute the human error [55]. While some studies discussed traffic mitigation techniques [56], AVs have a potential to decrease the capacity effectiveness and a decline in network performance under high-speed and high-flow situations [57]. Although AVs reduce car-ownership and increases car-sharing schemes, there is a potential for increasing the number of trips and their length and therefore contributing to the carbonization of the transportation system [58]. Some studies suggest that emissions reduction could not be substantial depending on the penetration level of AVs [52]. Elbanhawi et al. [59] examined traditional comfort methods and suggested factors for autonomous passenger awareness. The research indicated that there is a need to address passenger's comfort in AVs and [59]showed how loss of controllability in AVs will increase the likelihood of motion sickness. AVs face several challenges that hinder the use of AVs. These include technological errors such as software problems. Fundamentally, one of the main technological challenges is using machine learning techniques to handle uncertainties that characterize the driving environment while maintaining highest levels of safety [60]. Furthermore, software problems also include the moral dilemma of self-driving vehicles that is posed by accidents with inevitable deaths [61]. For instance, who is liable when a driverless car crashes? [62]. Dakić and Živković [63] presented an overview of the challenges for developing software in the field of AVs. The findings show a problematic phase of developing the software is the inability to influence ethics and morals of AVs by road users. Other problems include communication problems between AVs and human drivers. Färber [64] highlighted the issues of non-verbal communications, facial expressions and eye contact, as well as gestures and body movements all could be misinterpreted by AVs. These issues would create barriers to the implementation of AVs into the road networks. Likewise, there are some concerns with regard to explaining what AVs observe and why it makes such decisions to build reassurance with the passenger [65]. Another challenge for implementing AVs is the parking problem. This is due to the fact that the rise of AVs would create the opportunity to implement congestion pricing in urban centres [66]. This entails that congestion pricing should include a time-based charge for occupying the right of way, whether parked or in motion as well as energy-based charge from other externalities of driving [66]. There are several studies that address the implications of AVs on urban roads [67, 68, 69, 70, 71, 72, 73, 74, 75, 76]. Neves and Velez [77] reported that the existence of AVs in urban roads will have positive impact on road infrastructures, improvement of air quality, reduction of traffic congestion, and improvement of traffic safety and infrastructure capacity. Lu et al. [78] & Li and Wanger [79] suggested that the capacity of urban roads increases with AVs penetration rates. In addition, the results indicate a 16% increase in road capacity with artificial grid network at penetration ratio of 100% and 23% increase for the real road network. Zhang et al. [80] investigated learning-based predictive control (MPC) at freeway off-ramps, showing that proactive AV planning reduces risks at critical traffic In terms of road capacity increase, with 100% AVs penetration rates the road network could accommodate 40% more [81]. Primarily, there are two ways to test and predict AVs capabilities: microscopic and macroscopic approaches. The methods used to assess AV concerned studies include microsimulation modelling [82]. Most of the literature adopted AVs microsimulation modelling to examine their impact on road traffic performance [83, 84, 85, 86, 87, 88, 89, 90]. Nonetheless, some studies adopted a macroscopic approach [91, 92, 93, 94, 95].The AVs are still under development and hence using a microscopic modelling approach is ideal to reflect the interaction between traffic safety, RVs, and AVs. Even though there are few studies investigated the effects of AVs on urban road traffic safety [81, 96, 97], the literature is lacking relevant and applicable experimental research on the impacts of AVs and the automated vehicle technology on freeway safety [7, 14, 83, 98]. Nonetheless, few studies assessed the impacts of AVs on freeway safety. Therefore, this paper examines the effects of AVs on freeway safety. Moreover, this study is set to be pivotal and complementary to the literature.

3. Methodology

The purpose of this study is to assess the impacts of AVs on freeway traffic safety. In this research, certain metrics and assumptions have been adopted. The modelling involved in this study is based on the selected study area.

3.1. Study Area and Selection

Sheikh Mohamed Bin Zayed Road (E311) is one of the major roads in the UAE. It begins in Abu Dhabi and extends north-east towards Ras al-Khaimah. This study considered a section of the freeway E311 in Dubai, UAE as the test corridor. The selected section of the road is shown in Figure 1. This section of the road is about 10 km in length. Furthermore, the study area comprises of 6 junctions on the E311 that represent various layouts of junctions. Junctions 1 and 3 are right-in-right-out junctions. Junction 4 is a single point interchange, while junctions 2, 5, and 6 are full-overleaf junctions coupled with additional ramps to allow direct access for left turn movements. Full-overleaf junctions require different lane change and manoeuvre forms to induce traffic perturbations and hence, make this section of the road most ideal for freeway performance testing.

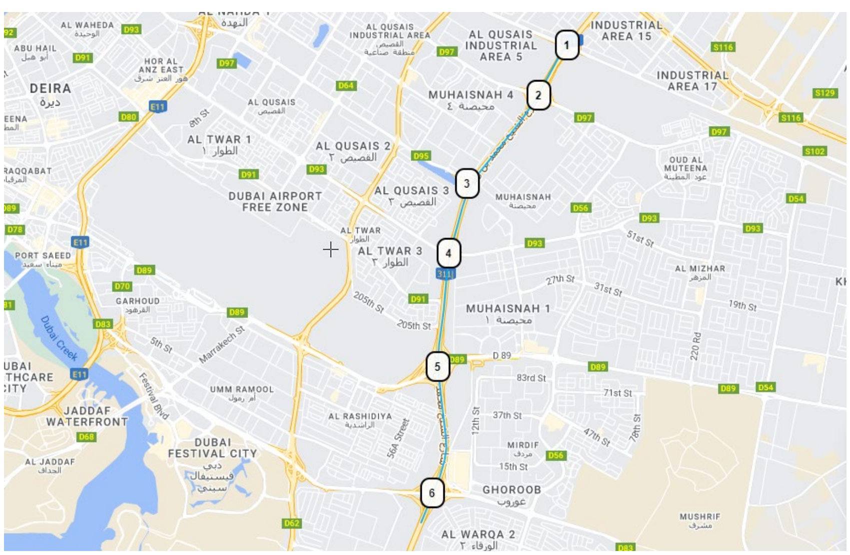

Fig. 1: The study area

3.2. Model Development and Simulation Environment

To better assess the influence of AVs on freeway traffic safety, this research adopted a microsimulation approach. The software adopted in this experiment is PTV VISSIM, where it is employed to develop a mixed traffic microsimulation model comprised of RVs and AVs. VISSIM includes two car following models: Wiedemann 74 and Wiedemann 99. While Wiedemann 74 is suitable for urban roads, Wiedemann 99 is designed for motorways traffic [99]. RVs and AVs have different driving behaviours and hence each has to be modelled accordingly. To successfully model each type, some parameters have to be adjusted and modified. The factors that impact the microscopic nature of traffic simulations are lane changing and lateral behaviour as well as car following on VISSIM [100]. Lane changing models are concerned with the acceptable time to perform a lane change. Car following models are intended to control vehicle's longitudinal speed and acceleration. For the purpose of this experiment, a microsimulation model was developed based on the study area to assess the impacts of AVs on traffic safety. Table 1 shows the parameters adopted in this study.

Table 1: Parameters for modelling RVs and AV

	Parameters	RVs (default)	AVs
Car-following (Wiedemann 99)	CC0 - Standstill distance (m)	1.5	0.5
	CC1 - Headway time (s)	0.9	0.3
Lane change	Min. headway (m)	0.5	0.2
	Safety reduction factor (%)	60	25
Driving characteristics	Look ahead distance (m)	0 to 250	0 to 500
	Look back distance (m)	0 to 150	0 to 300
	Observed vehicles	2	10
	Desired speed (kph)	110	110
Automated driving (platooning)	Max. number of vehicles	N/A	10
	Max. desired speed (kph)	N/A	110

3.3. Experimental Design

The microscopic VISSIM model is utilized to simulate different traffic conditions, as follows:

- Demand-to-capacity (D/C) ratios of the traffic demand on the road network: 7 levels of traffic conditions are considered [0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2]. These D/C ratios represent uncongested traffic conditions [0.6, 0.7], congested traffic conditions [0.8, 0.9], very congested traffic conditions [1.0], and oversaturated traffic conditions [1.1, 1.2].
- AVs penetration level (% of AVs): 10 penetration levels of AVs are considered [0%, 5%, 10%, 15%, 20%, 25%, 40%, 60%, 80%, 100%]. The percentages of [5%, 10%, 15%] represent little penetration of AVs in the traffic mix. The percentages [20%, 25%, 40%] represent moderate penetration of AVs in the traffic mix. The percentages [60%, 80%] and [100%] represent high to full penetration of AVs in the traffic mix, respectively.

3.4. Scenario Description and Run

Based on the aforementioned parameters and criteria, a total of 7 D/C ratios and 10 simulating mode share values are considered. The test results required a total of 70 microsimulation scenarios. In addition, each scenario is simulated 5 times and the trimmed averaged of the three middle values is considered the average result [101, 102, 103]. Each run extends to 5400 seconds (1.5 hours). The results were collected from time span 900–5400 seconds (1 hour) and 0.5-hour warmup period (15 minutes at the beginning and 15 minutes at the end). The warmup period is crucial to the microsimulation to eliminate any start-up periods (that start with an empty traffic system) and saturate the traffic system.

4. Results and Discussions

In each of the simulated scenarios, the impact of AVs on freeway safety was assessed through the reduction in traffic accidents. The experimental design involved simulating traffic accidents by adopting a vehicle gap set to a negative value, highlighting the risk posed by vehicles following each other more closely than the desired safety distance, as indicated by source [104]. The scenario with 0% AV penetration served as the baseline for comparison. In each simulation, the number of accidents at various levels of AV penetration was compared to this baseline, illustrating the percentage reduction in accidents. Figures 2 and 3 detail the impacts of AVs on decreasing traffic accidents under different traffic conditions. Figure 2 addresses undersaturated conditions with D/C ratios ranging from 0.6 to 0.9, while Figure 3 deals with oversaturated conditions at D/C ratios of 1.0, 1.1, and 1.2. In these figures, the x-axis represents the AV penetration rate, whereas the y-axis indicates the percentage reduction in potential accidents. Notably, with 0% AV penetration, there is no reduction in accidents, as this setup represents the benchmark scenario without AV implementation. Conversely, at 100% AV penetration, the reduction in the number of potential accidents reaches 100% across all D/C ratios. A significant observation from the data is that higher AV penetration rates correspond with fewer potential accidents. There is a consistent trend across all D/C ratios, with the most substantial accident reductions observed at 40%, 60%, 80%, and 100% AV penetration levels, where reductions range from 70% to 100%. This trend underscores the effectiveness of AV technology in enhancing freeway safety by mitigating collision risks under both undersaturated and oversaturated conditions.

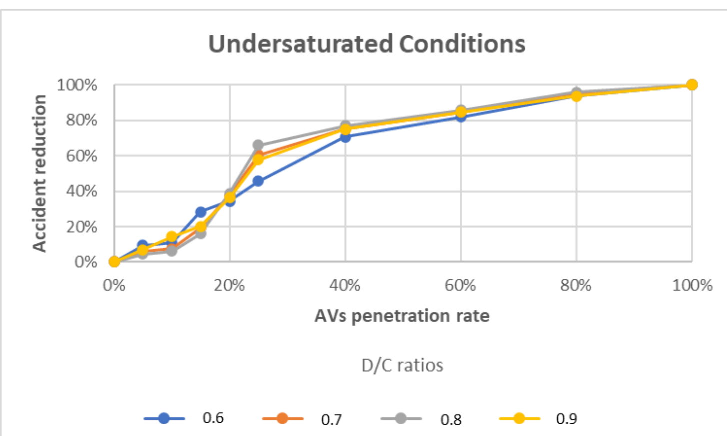

Fig. 2: Impact of AV penetration on traffic safety in undersaturated conditions

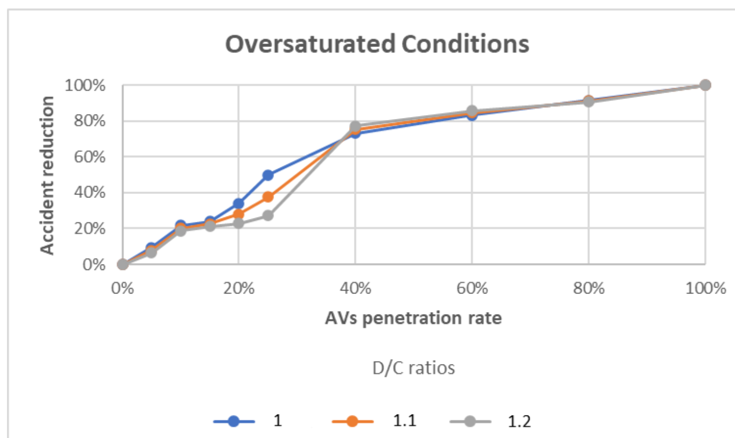

Fig. 3: Impact of AV penetration on traffic safety in oversaturated conditions

4. Conclusions and Future Work

This research explored the influence of AVs on freeway safety by examining the reduction of traffic accidents. Employing a microsimulation method with VISSIM, the study simulated a range of traffic scenarios to evaluate freeway safety. The experimental design encompassed seven D/C ratios (0.7, 0.8, 0.9, 1.0, 1.1, 1.2) and ten AV penetration rates (0%, 5%, 10%, 15%, 20%, 25%, 40%, 60%, 80%, 100%). Existing literature connects freeway traffic accidents to variables such as D/C ratios and AV penetration rates, establishing a foundational context for this analysis. The findings of this investigation indicate a consistent decline in the number of traffic accidents as AV penetration increases. Remarkably, the results suggest the potential for eliminating all traffic accidents in various traffic conditions—from uncongested to oversaturated—by fully integrating AVs on freeways and removing human driver interactions. Specifically, the most significant reductions in potential accidents were observed at AV penetration rates of 40%, 60%, 80%, and 100%, with reductions ranging between 70% and 100%. Despite these promising results, the study acknowledges several limitations. The predictions regarding AV capabilities were based on current technology, at a time when AVs have not yet achieved widespread adoption and their technological traits might not fully reflect future realities. This raises concerns about the accuracy of the microsimulation model in capturing the true characteristics of AVs. Future research should explore alternative simulation software to enhance the accuracy of predictions and evaluate the implications of AVs for freeway traffic safety more robustly. Moreover, as AV technology continues to advance and mature, many of the currently used parameters may evolve, leading to new findings and insights that could further inform the development and integration of AVs on freeways.

Data Availability
The VISSIM data used to support this work are available upon request from the authors

Acknowledgements
The authors would like to acknowledge the efforts of Dr. Osama ElSalhly for his aid in conducting microsimulations. Furthermore, the authors would appreciatively acknowledge Eng. Majed Marzouk for his assistance.

Conflicts of Interest
The authors declare no conflicts of interest concerning the publication of this paper.

References

[1] S. K. Gahrig and F. J. Stein, "Dead Reckoning and Cartography Using Stereo Vision for an Autonomous Car."Proceedings of the 1999 IEEGRSJ International Conference on Intelligent Robots and Systems," in *Intelligent Robots and Systems*, Kyongju, Soth Korea, 1999.

[2] A. Novikov, A. Shevtsova and V. Vasilieva, "Development of approach to reduce number of accidents caused by drivers," *Transportation Research Procedia,* vol. 50, pp. 491-498, 2020.

[3] Đ. Petrović, R. Mijailović and D. Pešić, "Traffic Accidents with Autonomous Vehicles: Type of Collisions, Manoeuvres and Errors of Conventional Vehicles' Drivers," *Transportation Research Procedia,* vol. 45, pp. 161-168, 2020.

[4] Department for Transport, "Pathway to Driverless Cars: Proposals to support advanced driver assistance systems and automated vehicle technologies," Centre for Connected & Autonomous Vehicles , London, 2016.

[5] NHTSA, "Traffic Safety Facts: Summary of Motor Vehicle Crashes," U.S Department of Transportation , Washington DC, 2016.

[6] National Highway Traffic Safety Administration, "Automated Vehicles for Safety," NHTSA, 2018. [Online]. Available: https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety. [Accessed 18 March 2022].

[7] P. Bansal and K. M. Kockelman, "Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies," *Transportation Research Part A,* vol. 95, pp. 49-63, 2017.

[8] Y. Lee and J. H. Mirman, "Parents' perspectives on using autonomous vehicles to enhance children's mobility," *Transportation Research Part C: Emerging Technologies,* vol. 96, pp. 415-431, 2018.

[9] V. Nagy and B. Horv'ath, "The effects of autonomous buses to vehicle scheduling system," *Procedia Computer Science,* vol. 170, pp. 235-240, 2020.

[10] D. J. Fagnant and K. Kockelman, "Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations for capitalizing on self-driven vehicles," *Transportation Research Part A,* vol. 77, pp. 167-181, 2015.

[11] State of California Department of Motor Vehicles, "Testing of Autonomous Vehicles with a Driver," State of California Department of Motor Vehicles, 2019. [Online]. Available: https://www.dmv.ca.gov/ portal/dmv/detail/vr/autonomous/testing. [Accessed 23 March 2022].

[12] M. Al-Turki, N. T. Ratrout, S. M. Rahman and I. Reza, "Impacts of Autonomous Vehicles on Traffic Flow Characteristics under Mixed Traffic Environment: Future Perspectives," *Sustainability, 13(19), 11052; https://doi.org/10.3390/su131911052,* pp. 1-22, 2021.

[13] K. M. Wilson, S. Yang, T. Roady, J. Kuo and M. G. Lenné, "Driver trust & mode confusion in an on-road study of level-2 automated vehicle technology," *Safety Science,* vol. 130, pp. 1-11, 2020.

[14] H. Yu, S. Tak, M. Park and . H. Yeo, "Impact of Autonomous-Vehicle-Only Lanes in Mixed Traffic Conditions," *Transportation Research Record,* pp. 1-10, 2019.

[15] W. Weijermars, A. Hula, A. Chaudhry, S. Sha , R. d. Zwart, C. Mons and . H. Boghani, "LEVITATE: Road safety impacts of Connected and Automated Vehicles," LEVITATE, Loughborough, 2020.

[16] P. Tafidis, H. Farah, T. Brijs and A. Pirdavania, "Safety implications of higher levels of automated vehicles: a scoping review," *Transport Reviews,* vol. 42, no. 2, pp. 245-267, 2022.

[17] M. M. Morando, Q. Tian, L. T. Truong and H. L. Vu, "Studying the Safety Impact of Autonomous Vehicles Using Simulation-Based Surrogate Safety Measures," *Journal of Advanced Transportation,* pp. 1-11, 2018.

[18] X. Tan and Y. Zhang, "A Computational Cognitive Model of Driver Response Time for Scheduled Freeway Exiting Takeovers in Conditionally Automated Vehicles," *The Journal of the Human Factors and Ergonomics Society,* vol. 66, no. 5, pp. 1583-1599, 2022.

[19] M. Kerimov, R. Safiullin, A. Marusin and A. Marusin, "Evaluation of Functional Efficiency of Automated Traffic Enforcement Systems," *Transportation Research Procedia,* vol. 20, pp. 288-294, 2017.

[20] A. Kamel, T. Sayed and C. Fua, "Real-time safety analysis using autonomous vehicle data: a Bayesian hierarchical extreme value model," *Transportmetrica B: Transport Dynamics,* vol. 11, no. 1, pp. 826-846, 2023.

[21] H. Deng, Y. Zhao, Q. Wang and A.-T. Nguyen , "Deep Reinforcement Learning Based Decision-Making Strategy of Autonomous Vehicle in Highway Uncertain Driving Environments," *Automotive Innovation,* vol. 6, p. 438–452, 2023.

[22] M. A. S. Kamal, J.-i. Imura, T. Hayakawa, A. Ohata and K. Aihara, "A Vehicle-Intersection Coordination Scheme for Smooth Flows of Traffic Without Using Traffic Lights," *IEEE Transactions on Intelligent Transportation Systems,* vol. 16, no. 3, p. 1136–1147, 2015.

[23] O. Mohammed and T. Arpad, "Macroscopic Traffic Simulation of Autonomous Vehicle Effects," *Vehicles ,* vol. 3, no. 2, pp. 187-196, 2021.

[24] M. Fujiu, Y. Morisaki and J. Takayama, "Impact of Autonomous Vehicles on Traffic Flow in Rural and Urban Areas Using a Traffic Flow Simulator," *Sustainability,* vol. 16, no. 2, p. no.658, 2024.

[25] "Safe, Efficient, and Comfortable Reinforcement-Learning-Based Car-Following for AVs with an Analytic Safety Guarantee and Dynamic Target Speed," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2678, no. 1, p. 643–661, 2023.

[26] BITRE, "Fatal road crashes in Australia in the 1990s and 2000s: crash types and major factors," Bureau of Infrastructure, Transport and Regional Economics, Canberra, Australia, 2011.

[27] S. E. Shladover, "Cooperative (rather than autonomous) vehicle-highway automation systems," *IEEE Intelligent Transportation Systems Magazine,* vol. 1, no. 1, p. 10–19, 2009.

[28] NHTSA, "National Motor Vehicle Crash Causation Survey," National Highway Trafc Safety Administration, U.S. Department of Transportation, 2008.

[29] L. T. Truong, C. . D. Gruyter, G. Currie and A. Delbosc , "Estimating the trip generation impacts of autonomous vehicles on car travel in Victoria, Australia," *Transportation,* vol. 44, no. 6, p. 1279–1292, 2017.

[30] S. Childress, B. G. Nichols, B. Charlton and S. E. Coe, "Using an Activity-Based Model to Explore the Potential Impacts of Automated Vehicles," *Transportation Research Record Journal of the Transportation Research Board,* vol. 2493, p. 99–106, 2015.

[31] D. Milakis, B. v. Arem and B. v. Wee, "Policy and society related implications of automated driving: A review of literature and directions for future research," *Journal of Intelligent Transportation Systems ,* vol. 21, no. 4, p. 324–348, 2017.

[32] S. A. Bagloee, M. Tavana, M. Asadi and T. Oliver, "Autonomous vehicles: challenges, opportunities, and future," *Journal of Modern Transportation,* vol. 24, no. 4, p. 284–303, 2017.

[33] H. Y. Makahleh , E. J. S. Ferranti and D. Dissanayake, "Assessing the Role of Autonomous Vehicles in Urban Areas: A Systematic Review of Literature," *Future Transportation,* vol. 4, no. 2, pp. 321-348, 2024.

[34] K. Dresner and P. Stone, "Multiagent Traffic Management: A Reservation-Based Intersection Control Mechanism," in *Proceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems*, New York, NY, USA, 2004.

[35] K. Dresner and P. Stone, "Sharing the Road: Autonomous Vehicles Meet Human Drivers," in *Proceedings of the 20th International Joint Conference on Artificial Intelligence*, Hyderabad, India, 2007.

[36] J. S. Brar and B. Caulfield, "Impact of autonomous vehicles on pedestrians' safety," in *IEEE 20th International Conference on Intelligent Transportation Systems (ITSC)*, Yokohama, Japan, 2017 .

[37] J. Lee, D. Lee, Y. Park, S. Lee and T. Ha, "Autonomous vehicles can be shared, but a feeling of ownership is important: Examination of the influential factors for intention to use autonomous vehicles," *Transportation Research Part C: Emerging Technologies,* vol. 107, pp. 411-422, 2019.

[38] S. Das, "Autonomous vehicle safety: Understanding perceptions of pedestrians and bicyclists," *Transportation Research Part F: Traffic Psychology and Behaviour,* vol. 81, pp. 41-54, 2021.

[39] S. Sohrabi, H. Khreis and D. Lord, "Impacts of Autonomous Vehicles on Public Health: A Conceptual Model and Policy Recommendations," *Sustainable Cities and Society,* vol. 63, no. 102457, 2020.

[40] D. Rojas-Rueda, M. Nieuwenhuijsen and H. Khreis, "1859 - Autonomous Vehicles and Public Health: Literature Review," *Journal of Transport & Health,* vol. 5, p. S13, 2017.

[41] S. Sohrabi, B. Dadashova, H. Khreis, I. N. Sener and J. Zmud, "Quantifying the health and health equity impacts of autonomous vehicles: A conceptual framework and literature review," *Journal of Transport & Health,* vol. 22, pp. 101-120, 2021.

[42] S. Pettigrew, "Why public health should embrace the autonomous car," *Australian and New Zealand Journal of Public Health,* vol. 41, no. 1, pp. 5-7, 2016.

[43] S. Pettigrew, . Z. Talati and R. Norman, "The health benefits of autonomous vehicles: public awareness and receptivity in Australia," *Australian and New Zealand Journal of Public Health ,* vol. 42, no. 5, pp. 480-483, 2018.

[44] T. Bellet, S. Laurent, J.-C. Bornard, I. Hoang and B. Richard, "Interaction between pedestrians and automated vehicles: Perceived safety of yielding behaviors and benefits of an external human–machine interface for elderly people," *Frontiers in Psychology,* vol. 13, 2022.

[45] P. Tafidis and A. Pirdavanib , "Application of surrogate safety measures in higher levels of automated vehicles simulation studies: A review of the state of the practice," *Traffic Injury Prevention,* vol. 24, no. 3, pp. 279-286, 2023.

[46] R. Utriainen, "The potential impacts of automated vehicles on pedestrian safety in a four-season country," *Journal of Intelligent Transportation Systems ,* vol. 25, no. 2, pp. 188-196, 2021.

[47] P. G. Saranti and D. Chondrogianni, "Autonomous vehicles (AVS): Effect on Pedestrian Safety," in *7th Road Safety Conference*, 2019.

[48] T. Stoiber, I. Schubert, R. Hoerler and P. Burger, "Will consumers prefer shared and pooled-use autonomous vehicles? A stated choice experiment with Swiss households," *Transportation Research Part D: Transport and Environment,* vol. 71, pp. 265-282, 2019.

[49] M. Shatanawi and F. Mészáros, "Implications of the Emergence of Autonomous Vehicles and Shared Autonomous Vehicles: A Budapest Perspective," *Sustainability,* vol. 14, no. 17, pp. 1-19, 2022.

[50] A. Pakzadnia and Y. Hassan, "Expected Safety Performance of Different Freeway Merging Strategies in an Environment of Mixed Vehicle Technologies," *Journal of Transportation Engineering, Part A: Systems,* vol. 149, no. 2, 2022.

[51] A. Jung, Y. Jo, J. Park and D. Yun, "A Multi-Agent Driving-Simulation Approach for Characterizing Hazardous Vehicle Interactions between Autonomous Vehicles and Manual Vehicles," *Applied Sciences,* vol. 14, no. 4, p. no. 1468, 2024.

[52] Ó. Silva, R. Cordera, E. González-González and S. Nogués, "Environmental impacts of autonomous vehicles: A review of the scientific literature," *Science of The Total Environment,* vol. 830, pp. 1-11, 2022.

[53] A. Hula, L. Snapp, J. Alson and K. Simon, "The Environmental Potential of Autonomous Vehicles," in *Road Vehicle Automation 4*, Springer, Cham, 2017, p. pp 89–95.

[54] A. D. Tibljaš , T. Giuffrè, S. Surdonja and S. Trubia , "Introduction of Autonomous Vehicles: Roundabouts Design and Safety Performance Evaluation," *MDPI,* vol. 10, no. 4, pp. 1-14, 2018.

[55] K. Othman, "Exploring the implications of autonomous vehicles: a comprehensive review," *Innovative Infrastructure Solutions,* vol. 165, no. 7, pp. 1-32, 2022.

[56] "The Swedish Traffic-Conflicts Technique," in *International Calibration Study of Traffic Conflict Techniques*, Sweden, 1984.

[57] Atkins, "Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow: Evidence Review," Department for Transport , London, 2016.

[58] P. M. Bösch, F. Becker, H. Becker and K. W. Axhausen, "Cost-based analysis of autonomous mobility services," *Transport Policy,* vol. 64, pp. 76-91, 2018.

[59] M. Elbanhawi, M. Simic and R. Jazar, "In the Passenger Seat: Investigating Ride Comfort Measures in Autonomous Cars," *IEEE Intelligent Transportation Systems Magazine,* vol. 7, no. 3, 2015.

[60] P. Mallozzi, P. Pelliccione, A. Knauss, C. Berger and N. Mohammadiha, "Autonomous Vehicles: State of the Art, Future Trends, and Challenges," in *Automotive Systems and Software Engineering*, Springer, Cham, 2019, p. 347–367.

[61] C. . Q. Choi, "The Moral Dilemmas of Self-Driving Cars," 25 October 2018. [Online]. Available: https://www.insidescience.org/news/moral-dilemmas-self-driving-cars. [Accessed 17 06 2022].

[62] E. Awad, S. Dsouza, R. Kim, J. Schulz, J. Henrich, A. Shariff, J.-F. Bonnefon and I. Rahwan, "The Moral Machine experiment," *Nature,* vol. 563, p. 59–64, 2018.

[63] P. Dakić and M. Živković, "An overview of the challenges for developing software within," in *ECBS 2021: 7th Conference on the Engineering of Computer Based Systems*, New York, NY, United States, 2021.

[64] B. Färber, "Communication and Communication Problems Between Autonomous Vehicles and Human Drivers," in *Autonomous Driving*, 2016, pp. 125-144.

[65] R. McAllister, Y. Gal, A. Kendall, M. v. d. Wilk, A. Shah, R. Cipolla and A. Weller, "Concrete Problems for Autonomous Vehicle Safety: Advantages of Bayesian Deep Learning," in *Twenty-Sixth International Joint Conference on Artificial Intelligence (IJCAI-17*.

[66] A. Millard-Ball, "The autonomous vehicle parking problem," *Transport Policy,* vol. 75, pp. 9-108, 2019.

[67] C. Zhao, F. Liao, X. Li and Y. Du, "Macroscopic modeling and dynamic control of on-street cruising-for-parking of autonomous vehicles in a multi-region urban road network," vol. 128, no. 103176, 2021.

[68] F. Duarte and C. Ratti, "The Impact of Autonomous Vehicles on Cities: A Review," *Journal of Urban Technology ,* vol. 25, no. 4, 2018.

[69] B. Farooq, E. Cherchi and A. Sobhani, "Virtual Immersive Reality for Stated Preference Travel Behavior Experiments: A Case Study of Autonomous Vehicles on Urban Roads," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2672, no. 50, 2018.

[70] D. Yamamoto, N. Suganuma and . K. Yoneda, "Localization for autonomous driving on urban road," in *International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS)*, Okinawa, Japan, 2015.

[71] J. Pérez, V. Milanés, T. d. Pedro and L. Vlacic, "Autonomous driving manoeuvres in urban road traffic environment: a study on roundabouts," *IFAC Proceedings Volumes,* vol. 44, no. 1, pp. 13795-13800, 2011.

[72] N. Suganuma and D. Yamamoto, "Map based localization of autonomous vehicle and its public urban road driving evaluation," in *2015 IEEE/SICE International Symposium on System Integration (SII)*, Nagoya, Japan, 2015.

[73] J. Parkin, "Autonomous vehicle interactions in the urban street environment: a research agenda," *Proceedings of the Institution of Civil Engineers - Municipal Engineer,* vol. 171, no. 1, pp. 15-25, 2018.

[74] S. Patella, F. Scrucca, F. Asdrubalia and S. Carresea, "Carbon Footprint of autonomous vehicles at the urban mobility system level: A traffic simulation-based approach," *Transportation Research Part D: Transport and Environment,* vol. 74, pp. 189-200, 2019.

[75] C. Gasparinatou, M. G. Oikonomou, A. Tympakanaki, J. Casas, T. Djukic, E. I. Vlahogianni and G. Yannis, "Passenger Car Unit Values of Connected Autonomous Vehicles in," 2021.

[76] A. Broggi, P. Cerri, S. Debattisti, M. C. Laghi, P. Medici, M. Panciroli and A. Prioletti, "PROUD-Public road urban driverless test: Architecture and results," in *IEEE Intelligent Vehicles Symposium Proceedings*, Dearborn, MI, USA, 2014.

[77] J. Neves and J. Velez, "The impacts of autonomous vehicles on urban road," *Dossier,* vol. 20, pp. 1-6, 2018.

[78] Q. Lu, T. Tettamantia, D. Hörcherb and I. Vargaa, "The impact of autonomous vehicles on urban traffic network capacity: an experimental analysis by microscopic traffic simulation," *The International Journal of Transportation Research,* vol. 12, no. 8, pp. 540-549, 2019.

[79] D. Li and P. Wagner, "Impacts of gradual automated vehicle penetration on motorway operation: a comprehensive evaluation," *European Transport,* vol. 36, no. 11, pp. 1-10, 2019.

[80] X. Qi, L. Zhang, P. Wang, J. Yang, T. Zou and W. Liu, "Learning-based MPC for Autonomous Motion Planning at Freeway Off-ramp Diverging," *IEEE Transactions on Intelligent Vehicles,* pp. 1-11, 2024.

[81] J. E. Park, W. Byun, Y. Kim, H. Ahn and D. K. Shin, "The Impact of Automated Vehicles on Traffic Flow and Road Capacity on Urban Road Networks," *Journal of Advanced Transportation,* pp. 1-10, 2021.

[82] H. U. Ahmed , Y. Huang and P. Lu, "A Review of Car-Following Models and Modeling Tools for Human and Autonomous-Ready Driving Behaviors in Micro-Simulation," *MDPI,* no. 4, pp. 315-335, 2021.

[83] Y. Ko, J. . H. Rho and D. Yook, "Assessing Benefits of Autonomous Vehicle System Implementation through the Network Capacity Analysis," *The Korea Spatial Planning Review,* vol. 93, pp. 17-24, 2017.

[84] B. Friedrich, "The effect of autonomous vehicles on traffic," in *Autonomous Driving*, Berlin , Springer, 2016, pp. 317-334.

[85] A. Talebpour, H. S. Mahmassani and A. Elfar, "nvestigating the Effects of Reserved Lanes for Autonomous Vehicles on Congestion and Travel Time Reliability," *Journal of the Transportation Research Board,* vol. 2622, no. 1, pp. 1-12, 2017.

[86] S. C. Calvert, W. J. Schakel and J. W. C. v. Lint, "Will Automated Vehicles Negatively Impact Traffic Flow?," *Journal of Advanced Transportation,* pp. 1-17, 2017.

[87] "Highway Capacity Benefits from Using Vehicle-to-Vehicle Communication and Sensors for Collision Avoidance," in *2011 IEEE Vehicular Technology Conference (VTC Fall)*, San Francisco, CA, 2011.

[88] Y. Bichiou and H. A. Rakha, "Developing an optimal intersection control system for cooperative automated vehicles," *IEEE Transactions on ITS,* vol. 20, no. 5, pp. 1-9, 2018.

[89] S. Jones and B. H. Philips, "COOPERATIVE ADAPTIVE CRUISE CONTROL: CRITICAL HUMAN FACTORS ISSUES AND RESEARCH QUESTIONS," in *the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*, NY, USA, 2013.

[90] O. Kavas-Torris, . L. Nathan and L. Guvenc, "Simulating the Effect of Autonomous Vehicles on Roadway Mobility in a Microscopic Traffic Simulator," *International Journal of Automotive Technology,* p. 713–733, 2021.

[91] R. Desta and J. Toth, "Macroscopic Experiments on Coexistence of Autonomous Vehicle Behavior on Various Heterogeneous Traffic Conditions," *Journal of Advanced Transportation,* 2022.

[92] . W. Zhenyu, L. Liang, . G. Yang, X. Zhang, . J. Sun, D. Zhao and W. Gao , "A Novel Macro-Block Group Based AVS Coding Scheme for Many-Core Processor," *Journal of Signal Processing Systems,* p. 129–145, 2011.

[93] P. Fernandes, J. M. Bandeira and M. C. Coelho, "A macroscopic approach for assessing the environmental performance of shared, automated, electric mobility in an intercity corridor," *Journal of Intelligent Transportation Systems,* 2021.

[94] J. Ivanchev, A. Knoll, D. Zehe, S. Nair and D. Eckhoff , "A Macroscopic Study on Dedicated Highway Lanes for Autonomous Vehicles," in *ICCS 2019: Computational Science – ICCS 2019*, 2019.

[95] R. Desta and J. Tóth, "Evaluation of Autonomous Vehicles Effects based on Changing Driving Logics with Macroscopic Traffic Simulation".

[96] P. Fernandes and U. Nunes, "Platooning With IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow," *IEEE Transactions on ITS,* vol. 13, no. 1, pp. 91-106, 2012.

[97] I.-s. Park, J.-d. Lee, J.-y. Lee and K.-y. Hwang, "Impacts of automated vehicles on freeway traffic-flow," *Journal of 7e Korea Institute of Intelligent Transport Systems,* vol. 14, no. 6, pp. 21-36, 2015.

[98] S. Zang, M. Ding, D. Smith, P. Tyler, T. Rakotoarivelo and M. A. Kaafar, "The Impact of Adverse Weather Conditions on Autonomous Vehicles: How Rain, Snow, Fog, and Hail Affect the Performance of a Self-Driving Car," *IEEE Vehicular Technology Magazine ,* vol. 14, no. 2, pp. 103 - 111, 2019.

[99] PTV vision, "VISSIM 2020 user manual," 2020.

[100] M. El Sahly and A. Abdelfatah, "Effects of Automated Vehicles on Freeway Traffic Performance," *Wulfenia Journal,* vol. 27, no. 2, pp. 83-107, 2020.

[101] E. Aria, J. Olstam and C. Schwietering, "Investigation of Automated Vehicle Effects on Driver's Behavior and Traffic Performance," *Transportation Research Procedia,* vol. 15, pp. 761-770, 2016.

[102] U. Leyn and P. Vortisch, "Calibrating VISSIM for the German Highway Capacity Manual," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2483, no. 1, pp. 74-79, 2015.

[103] P. Bansal and K. M. Kockelman, "Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies," *Transportation Research Part A: Policy and Practice,* vol. 95, pp. 49-63, 2017.

[104] A. Abdelfatah, M. Marzouk, A. Garib and H. Al-Harthi, "Evaluating the Impact of Fog on Freeway Safety Using VISSIM," in *Road Safety and Simulation International Conference RSS2013*, Rome, Italy, 2013.