Research Article

The Impact of Increasing Traffic Volume on Autonomous Vehicles in Roundabout

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Abstract: This study employs the PTV VISSIM simulation software to investigate the impact of increasing traffic volumes on conventional vehicles and autonomous vehicles (AVs) with distinct behavioural traits: cautious, normal, and aggressive. The simulations cover a range of traffic volumes, from 100 to 600 vehicles, and measure the effects on travel time, emissions (CO, NOX, VOC), and fuel consumption. The results show that with increasing penetration rates of AVs, travel times generally decrease, with aggressive AVs achieving the shortest times, followed by normal, then cautious AVs. Emissions and fuel consumption also tend to decrease as the penetration rate of AVs increases. Notably, the results demonstrate that aggressive AVs excel in reducing travel time, while normal AVs consistently balance between efficiency and reduced emissions, and cautious AVs emphasize safety and lower emissions. Despite the differing behavioural traits, all AV types exhibit a marked improvement over conventional vehicles in terms of travel time, emissions, and fuel consumption. At every penetration rate, AVs lead to shorter travel times and lower emissions, with aggressive AVs being the most efficient, followed by normal and then cautious AVs. These findings emphasize the potential benefits of integrating autonomous vehicles into transportation networks. They suggest that optimizing AV behaviour, depending on the context and objectives, can lead to more efficient, environmentally friendly traffic systems. The study offers valuable insights for policymakers, urban planners, and researchers aiming to leverage the distinct strengths of each AV behaviour to create a more sustainable and efficient future for autonomous transportation.

Keywords: PTV VISSIM, Autonomous Vehicles, Roundabout Intersections, Travel Time, Emissions, Fuel Consumption.

Dönel Kavşakta Artan Trafik Hacminin Otonom Araçlar Üzerindeki Etkisi

Özet: Bu çalışma, PTV VISSIM benzetim programını kullanarak, artan trafik hacimlerinin sürücülü araçlarla birlikte farklı davranış özelliklerine sahip otonom araçlar (AV'ler) üzerindeki etkisini araştırmayı amaçlamaktadır. Benzetimler, 100 ile 600 araç arasındaki çeşitli trafik yoğunluklarını içermekte ve seyahat süreleri, emisyonlar (CO, NOX, VOC) ve yakıt tüketimi üzerindeki etkilerini ölçmektedir. Sonuçlar, AV'lerin yayılım oranlarının artmasıyla birlikte genellikle seyahat sürelerinin azaldığını göstermektedir; agresif AV'ler en kısa süreleri elde ederken, bunu normal ve ardından dikkatli AV'ler takip etmektedir. Emisyonlar ve yakıt tüketimi de AV'lerin yayılım oranı arttıkça azalma eğilimi göstermektedir. Özellikle, agresif AV'lerin seyahat süresini azaltmada etkili olduğu, normal AV'lerin verimlilik ve azalan emisyonlar arasında tutarlı bir denge sağladığı ve dikkatli AV'lerin güvenlik ve düşük emisyonları vurguladığı görülmektedir. Davranış özelliklerindeki farklılıklara rağmen, tüm AV türleri geleneksel araçlara kıyasla belirgin bir iyileşme sergilemektedir. Her yayılım oranında, AV'ler daha kısa seyahat süreleri ve daha düşük emisyonlara yol açmaktadır; agresif AV'ler en verimli olurken, bunu normal ve ardından dikkatli AV'ler takip etmektedir. Bu bulgular, otonom araçların ulaşım ağlarına entegre edilmesinin potansiyel faydalarını vurgulamaktadır. Bu durum, hedeflere ve koşullara bağlı olarak AV davranışlarının optimize edilmesinin, daha verimli ve çevre dostu trafik sistemlerinin oluşmasına olanak tanıyabileceğini öne sürmektedir. Çalışma, her bir AV davranışının farklı güçlü

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yönlerinden yararlanarak otonom ulaşım için daha sürdürülebilir ve verimli bir gelecek yaratmayı amaçlayan politika yapıcılar, şehir planlamacıları ve araştırmacılar için değerli içgörüler sunmaktadır.

Anahtar Kelimeler: PTV VISSIM, otonom araçlar, dönel kavşaklar, seyahat süresi, emisyonlar, yakıt tüketimi.

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1. Introduction

With the rapid development of autonomous vehicle technology, integrating these vehicles into our transportation networks represents a significant paradigm shift. As we advance toward this new era, it is crucial to understand how varying autonomous vehicle behaviours impact critical aspects such as travel time, exhaust emissions, and fuel consumption to achieve effective urban planning and sustainable mobility patterns (Khreis et al., 2016; Maheshwari & Axhausen, 2021; Sultana et al., 2021). This study employs PTV VISSIM simulation software to investigate the complex interactions between increased traffic volume and the introduction of autonomous vehicles exhibiting cautious, normal, and aggressive driving behaviours at roundabouts.

Circular intersections, commonly known as roundabouts, have garnered attention as efficient traffic management solutions. In the face of increasing vehicular traffic, exploring the implications of this surgeon's conventional traffic patterns and the evolving presence of assertive autonomous vehicle fleets becomes imperative. This investigation aims to comprehend the intricate dynamics at play, considering the circular layout of roundabouts and the evolving landscape of modern transportation (Mesionis et al., 2020; Shahandasht et al., 2019). Aggressive autonomous vehicles, which exhibit assertive driving behaviour, represent a unique dimension of this analysis (Dey et al., 2017; Karjanto et al., 2017; Schrum et al., 2024).

Using PTV VISSIM simulation tools enables a controlled and systematic exploration of different traffic scenarios (Alghamdi et al., 2022; Ullah et al., 2021). Analysing performance metrics under both autonomous vehicles and their conventional counterparts amid fluctuating traffic volumes adds to a more comprehensive understanding of the challenges and opportunities inherent in the dynamic evolution of the transportation landscape. This investigation seeks to uncover insights that inform urban planning, traffic management, and the ongoing discourse surrounding the integration of autonomous vehicles into our transportation networks.

The significance of this study lies in its unique contribution to the discourse on integrating and optimizing autonomous vehicles (AVs), distinguishing it from prior investigations. Unlike existing literature, this study enriches the ongoing dialogue and holds the potential to make substantial national and international scholarly contributions. Focusing on a roundabout in Kirkuk, Iraq, this research provides a comprehensive analysis of traffic dynamics, specifically examining the influence of increasing traffic volume and various types of AVs on travel time, emissions, and fuel consumption.

Our observations reveal distinct trends across different AV types—aggressive, normal, and cautious. Aggressive AVs exhibit the highest efficacy in reducing average travel time, particularly at higher penetration rates. Normal AVs strike a balance between efficiency and emissions reduction, while cautious AVs, prioritizing safety, also contribute to reduced travel time, albeit to a lesser extent compared to aggressive AVs, while demonstrating the lowest emissions among AV types.

2. Literature review

The study (Zhao et al., 2022) highlights growing interest in the environmental impact of connected automated vehicles (CAVs) on fuel consumption and traffic emissions. Studies confirm the ability of autonomous vehicles to significantly reduce environmental burdens, attributing this improvement to enhanced coordination of traffic flow and improved driving behaviours. Notably, CAV advantages are more pronounced in signalized intersections, critical points in urban traffic networks. Methodologically, car-following models (IDM, ACC, CACC) and the VT-micro model are commonly employed, showcasing the diverse approaches to assess CAVs' environmental implications effectively.

The examination by (Cao & Zöldy, 2020) delves into evaluating autonomous vehicle behaviour and its consequential effects on fuel consumption and emissions. Initial testing is conducted at ZalaZONE's roundabout, setting the stage for further comprehensive assessments. The study concentrates on autonomous vehicle conduct within roundabouts, scrutinizing driving behaviour, in-vehicle systems, roundabout parameters, and diverse vehicle types. Employing a method integrating driving cycles into the existing EPA test program, the authors meticulously construct scenario models using various simulation environments to capture the nuanced dynamics of autonomous vehicles in real-world scenarios.

The potential of vehicle platoons in reducing energy consumption and emissions is recognized (Zhang et al., 2023), with a distinction noted between ad hoc platoon formation, which increases fuel consumption and emissions, and dedicated Connected Autonomous Vehicle (CAV) lane strategies, which enhance fuel economy and emission reduction. This paper systematically investigates fuel consumption and emissions in mixed-traffic environments, emphasizing the negative impact of ad hoc platoon formation on these environmental metrics. Utilizing an extended cellular automaton model, the study compares ad hoc platoon formation and dedicated CAV lane strategies. Notably, the research underscores that while most platooning studies have traditionally focused on pure CAV environments, the detrimental effects of ad hoc platoon formation on fuel consumption and emissions remain a critical consideration in mixed traffic scenarios.

The investigation conducted by researchers into the effects of autonomous vehicles (AVs) on single-lane roundabouts has yielded noteworthy findings (Boualam et al., 2023). A microsimulation model and field data from a Győr, Hungary, roundabout were used in the study to investigate several scenarios with varying rates of AV market penetration. Approximately 10% and 20% more leg capacities might be achieved, respectively, with AV penetration rates of 20% and 40% in the traffic flow. Additionally, it was discovered that these AVs significantly decreased excessive queue durations. Researchers have studied how incorporating autonomous vehicles (AVs) into roundabouts affects traffic safety and road design (Deluka et al., 2018). The study has examined situations where autonomous vehicles (AVs) and conventional vehicles (CVs) are mixed using a microsimulation model and field data from roundabouts in Croatia. They have provided insights into possible changes in roundabout safety with the advent of autonomous vehicles (AVs) through simulations using the Surrogate Safety Assessment Model (SSAM). This emphasizes the necessity of revising road design guidelines and investigating potential safety measures to allow for the incorporation of autonomous vehicles.

This study not only adds valuable insights to the ongoing discourse on the integration and optimization of autonomous vehicles but also has the potential to make substantial contributions to both national and international literature. By providing a comprehensive analysis of traffic dynamics at a Kirkuk, Iraq, roundabout, the study offers valuable insights into the impact of increasing traffic volume and different types of autonomous vehicles (AVs) on travel time, emissions, and fuel consumption. The observed trends reveal that all autonomous vehicle types aggressive, normal, and cautious show a reduction in travel time, with aggressive AVs demonstrating the greatest capacity to minimize average travel time, particularly at higher penetration rates. Normal AVs provide a balanced approach, combining efficiency and reduced emissions. Cautious AVs, designed with safety as a priority, also contribute to reduced travel time, albeit to a lesser extent compared to aggressive AVs, while achieving the lowest emissions among the AV types. This comprehensive perspective underscores the sustainability benefits of integrating various types of autonomous vehicles into existing traffic systems. It also demonstrates the value of customizing AV behaviour to achieve specific outcomes whether it's reduced travel time, increased safety, or lower emissions. The role of these autonomous vehicles is emerging as a key factor in shaping the future of mobility. The findings presented here provide actionable insights for policymakers, urban planners, and researchers worldwide, showing how a mix of AV behaviours can contribute to a more efficient and environmentally friendly traffic system. As autonomous vehicle technology continues to evolve, this study's outcomes serve as a foundation for further research and decision-making on a global scale, contributing to a more sustainable future in transportation.

3. Materials and methods

3.1. Study Location

The intersection is situated in Kirkuk, Iraq. The roundabout's specific design characteristics and layout are illustrated in Figure 1 and Figure 2, providing a visual reference for readers to comprehend the intricacies of the study location.

Figure 1. Illustration of the geometric layout and design features of the selected roundabout in Kirkuk, Iraq. Sources: PTV VISSIM Model.

Figure 2. A visual representation highlighting the geographical context and placement of the roundabout within Kirkuk, Iraq. Sources: PTV VISSIM Model.

3.2. Data Collection

The data collection process for this study involved obtaining traffic volume data through a randomized approach, ranging from a total traffic volume of 100 to 600 vehicles, as illustrated in Table 1. This diverse range of traffic volumes aims to comprehensively assess the impact of varying traffic conditions on the selected roundabout in Kirkuk, Iraq.

Table 1. Studied Traffic Volume at the roundabout Intersection.

Bound	vehicles	Movement Ratio		
		Right	Straight	Left
North	25-150	0.333	0.333	0.333
East	25-150	0.333	0.333	0.333
South	25-150	0.333	0.333	0.333
West	25-150	0.333	0.333	0.333

Source: Processed data by author (2024).

3.3. Autonomous Vehicle and Human Behaviour Modelling

This study uses sophisticated modelling techniques to simulate the behaviours of autonomous vehicles (AVs) with distinct driving styles, aggressive, normal, and cautious alongside human-driven vehicles within a designated roundabout intersection. The modelling intricately captures the dynamics of these various driving styles, including their acceleration, deceleration, and decision-making processes. This comprehensive approach allows for an in-depth analysis of the potential impact each type of AV behaviour has on travel time, emissions, and fuel consumption.

Aggressive AVs exhibit assertive driving behaviours, such as high acceleration, rapid deceleration, and quick decision-making, typically designed for efficiency and speed. In contrast, normal AVs represent a balanced approach, with moderate driving patterns and decision-making processes that emphasize both efficiency and safety. Cautious AVs prioritize safety, with more gradual acceleration, conservative deceleration, and careful decision-making processes.

The study incorporates human behaviour modelling to simulate the driving patterns and decision-making processes of human drivers within the same traffic environment. This parallel modelling approach facilitates a comparative analysis, providing a nuanced understanding of how autonomous vehicles with differing driving styles interact with conventional human-driven vehicles. The insights gained from this analysis can help understand the implications of integrating autonomous vehicles into existing traffic systems, focusing on balancing efficiency, safety, and emissions.

PTV VISSIM, the software used in this study, excels at modelling both human and autonomous vehicle behaviours within traffic simulations. It accurately replicates the intricate dynamics of human drivers, including acceleration, deceleration, and decision-making, while also providing a robust framework for simulating the unique behaviours and interactions of autonomous vehicles. This dual modelling functionality positions PTV VISSIM as a comprehensive tool for studying the complex interactions between human-driven and autonomous vehicles in various traffic scenarios. This makes it invaluable for researching and understanding the evolving landscape of transportation, where autonomous vehicles with different driving behaviours increasingly play a significant role.

3.4. Speed Distributions

For the human-driven scenario, speeds were set randomly within the simulated traffic environment. The distribution of speeds for the human-driven scenario is visually depicted in Figure 3, providing insight into the varied velocities considered in the study.

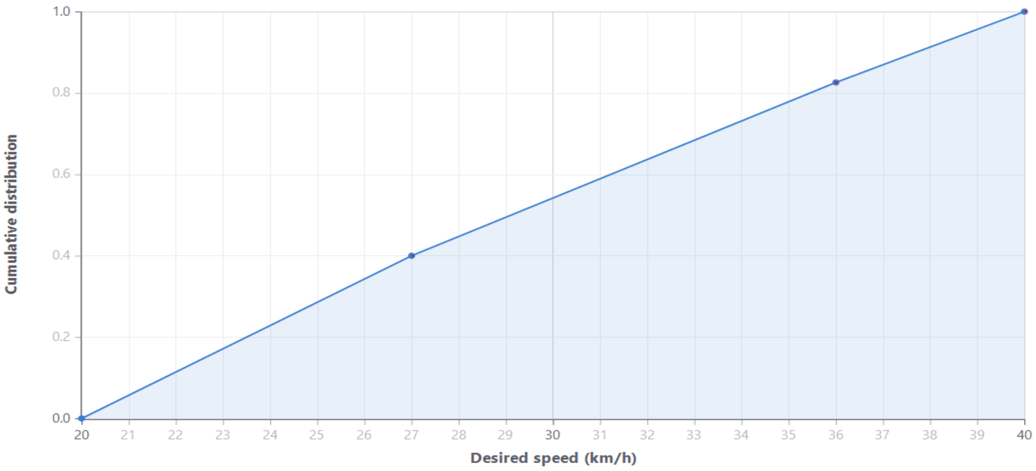

Figure 3. Intended Velocity Distribution of Conventional Passenger Vehicles. Sources: PTV VISSIM Model

In contrast, for the automated vehicles scenario, speed profiles were also established randomly to simulate the behavior of autonomous vehicles. The representation of these autonomous vehicle speeds is captured in Figure 4, offering a visual reference for the distribution of speeds in the automated scenarios. The randomized nature of both traffic volume and speed settings ensures a robust and unbiased exploration of the effects of increasing traffic volume on travel time, emissions, and fuel consumption in diverse driving scenarios.

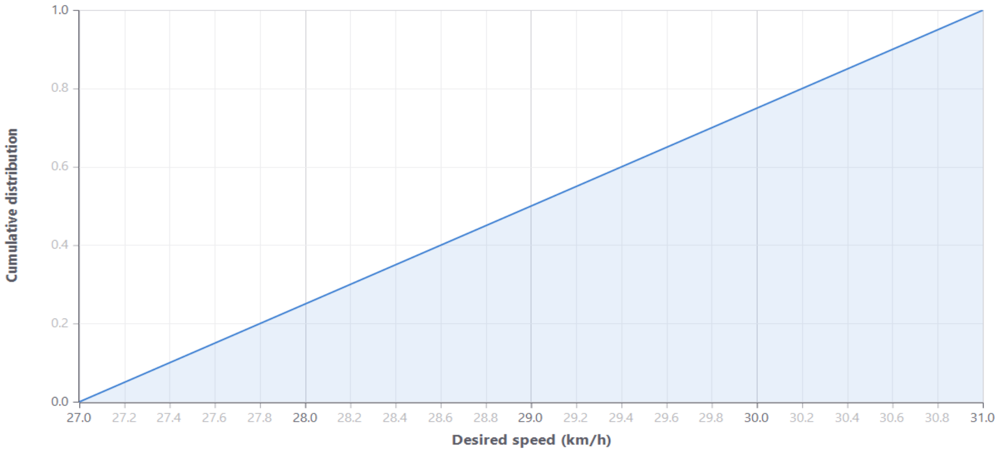

Figure 4. Intended Velocity Distribution of Autonomous Vehicles. Sources: PTV VISSIM Model

3.5. Car Following Models and Lane Change Models

The study delves into the nuanced realms of autonomous vehicle (AV) behavior, specifically focusing on aggressive driving mode. The background of AV aggressive behavior modeling involves intricate simulations that consider factors such as acceleration, deceleration, and decision-making processes unique to aggressive driving scenarios. This modeling is crucial for understanding the potential impact of aggressive AVs on traffic dynamics and overall system efficiency. In parallel, the study also incorporates human behavior modeling, simulating the driving patterns and decision-making processes of human drivers within the same traffic environment. This comparative analysis allows for a comprehensive assessment of how aggressive AVs interact with conventional human-driven vehicles, providing insights into potential scenarios that may unfold in mixed-traffic settings.

VISSIM incorporates two implementations of the Wiedemann car-following model: Wiedemann '99 and Wiedemann '74. While they share similarities, the primary distinction lies in the number of adjustable parameters, with Wiedemann '99 offering greater flexibility than the relatively fixed parameters in Wiedemann '74. The Wiedemann '99 model in VISSIM is calibrated based on driving behavior characteristics (CC), determined by regime categorization thresholds. As PTV Group (2018) outlined, Table 2 provides descriptions and default values for the CC parameters applicable to human-driven vehicles (HVs). Users can modify these parameters, including the number of observed vehicles, look-ahead distance, average standstill distance, and the additive and multiplicative components of the desired safety distance.

Table 2. Parameters Influencing Driving Behaviour in Car Following Models Within PTV VISSIM.

Wiedemann 99 following model parameters	AV cautious	AV normal	AV aggressive	Human
CC0 Standstill distance	1.50 m	1.50 m	1.00 m	1.50 m
CC1 Gap time distribution	1.5 s	0.9 s	0.6 s	0.9 s
CC2 'Following' distance oscillation	0.00 m	0.00 m	0.00 m	4.00 m
CC3 Threshold for entering 'Following'	-10.00	-8.00	-6.00	-8.00
CC4 Negative speed difference	-0.10	-0.10	-0.10	-0.35
CC5 Positive speed difference	0.10	0.10	0.10	0.35
CC6 Distance dependency of oscillation	0.00	0.00	0.00	11.44
CC7 Oscillation acceleration	0.10 m/s^2	0.10 m/s^2	0.10 m/s^2	0.25 m/s^2
CC8 Acceleration from standstill	3.00 m/s^2	3.50 m/s^2	4.00 m/s^2	3.50 m/s^2
CC9 Acceleration at 80 km/h	1.20 m/s^2	1.50 m/s^2	2.00 m/s^2	1.50 m/s^2

Sources: PTV VISSIM Model.

In VISSIM, lane changes are differentiated into two categories: the first pertains to essential lane changes, which occur in response to lane reduction, incidents, or when a vehicle needs to access a lane to turn at an upcoming intersection based on its destination. The associated parameter for necessary lane changes includes the maximum allowable deceleration for both the vehicle initiating the lane change and the trailing vehicle on the new lane. As the PTV Group (2018) outlined, Table 3 details the parameters related to necessary lane changes in VISSIM, providing their respective descriptions. The second type involves discretionary lane changes, wherein a vehicle changes lanes to achieve higher speed or secure more space. This process of discretionary lane changes follows a three-step sequence, commencing with the decision of whether to accept the lane change. Subsequently, the vehicle evaluates the feasibility of the intended lane change and executes a gap acceptance control (Osman, 2023).

Table 3. Parameters Governing Lane Change Behaviour in PTV VISSIM.

Parameter's	AV cautious	AV normal	AV aggressive	Human
Advanced merging	on	on	on	on
Cooperative Lane change	on	on	on	off
Safety distance reduction Factor	1.00 m	0.60	0.75	0.60 m
Min clearance (front/rear)	1.00 m	0.50 m	0.50 m	0.50 m
Maximum deceleration for Cooperative braking	-2.50 m/s^2	-3.00 m/s^2	-6.00 m/s^2	-3.00 m/s^2

Sources: PTV VISSIM Model.

3.6. Simulation Scenarios

The study encompasses 90 simulation scenarios, each tailored to specific combinations of traffic volume and penetration rates. the variations in traffic volume span from 100 to 600 vehicles, capturing diverse traffic conditions. Additionally, different penetration rates, ranging from 0% to 100%, are illustrated in Table 4.

Table 4. Overview of Study Scenarios.

Scenarios	Total Traffic Volume	Penetration of AV Cautious	Penetration of AV Normal	Penetration of AV aggressive	Penetration of Human
No. 1	100 Vehicle	0 %	0 %	0 %	100 %
No. 2	100 Vehicle	25 %	0 %	0 %	75 %
No. 3	100 Vehicle	50 %	0 %	0 %	50 %
No. 4	100 Vehicle	75 %	0 %	0 %	25 %
No. 5	100 Vehicle	100 %	0 %	0 %	0 %

No. 6	200 Vehicle	0 %	0 %	0 %	100 %
No. 7	200 Vehicle	25 %	0 %	0 %	75 %
No. 8	200 Vehicle	50 %	0 %	0 %	50 %
No. 9	200 Vehicle	75 %	0 %	0 %	25 %
No. 10	200 Vehicle	100 %	0 %	0 %	0 %
No. 11	300 Vehicle	0 %	0 %	0 %	100 %
No. 12	300 Vehicle	25 %	0 %	0 %	75 %
No. 13	300 Vehicle	50 %	0 %	0 %	50 %
No. 14	300 Vehicle	75 %	0 %	0 %	25 %
No. 15	300 Vehicle	100 %	0 %	0 %	0 %
No. 16	400 Vehicle	0 %	0 %	0 %	100 %
No. 17	400 Vehicle	25 %	0 %	0 %	75 %
No. 18	400 Vehicle	50 %	0 %	0 %	50 %
No. 19	400 Vehicle	75 %	0 %	0 %	25 %
No. 20	400 Vehicle	100 %	0 %	0 %	0 %
No. 21	500 Vehicle	0 %	0 %	0 %	100 %
No. 22	500 Vehicle	25 %	0 %	0 %	75 %
No. 23	500 Vehicle	50 %	0 %	0 %	50 %
No. 24	500 Vehicle	75 %	0 %	0 %	25 %
No. 25	500 Vehicle	100 %	0 %	0 %	0 %
No. 26	600 Vehicle	0 %	0 %	0 %	100 %
No. 27	600 Vehicle	25 %	0 %	0 %	75 %
No. 28	600 Vehicle	50 %	0 %	0 %	50 %
No. 29	600 Vehicle	75 %	0 %	0 %	25 %
No. 30	600 Vehicle	100 %	0 %	0 %	0 %
No. 31	100 Vehicle	0 %	0 %	0 %	100 %
No. 32	100 Vehicle	0 %	25 %	0 %	75 %
No. 33	100 Vehicle	0 %	50 %	0 %	50 %
No. 34	100 Vehicle	0 %	75 %	0 %	25 %
No. 35	100 Vehicle	0 %	100 %	0 %	0 %
No. 36	200 Vehicle	0 %	0 %	0 %	100 %
No. 37	200 Vehicle	0 %	25 %	0 %	75 %
No. 38	200 Vehicle	0 %	50 %	0 %	50 %
No. 39	200 Vehicle	0 %	75 %	0 %	25 %
No. 40	200 Vehicle	0 %	100 %	0 %	0 %
No. 41	300 Vehicle	0 %	0 %	0 %	100 %
No. 42	300 Vehicle	0 %	25 %	0 %	75 %
No. 43	300 Vehicle	0 %	50 %	0 %	50 %
No. 44	300 Vehicle	0 %	75 %	0 %	25 %
No. 45	300 Vehicle	0 %	100 %	0 %	0 %
No. 46	400 Vehicle	0 %	0 %	0 %	100 %
No. 47	400 Vehicle	0 %	25 %	0 %	75 %
No. 48	400 Vehicle	0 %	50 %	0 %	50 %
No. 49	400 Vehicle	0 %	75 %	0 %	25 %
No. 50	400 Vehicle	0 %	100 %	0 %	0 %
No. 51	500 Vehicle	0 %	0 %	0 %	100 %
No. 52	500 Vehicle	0 %	25 %	0 %	75 %
No. 53	500 Vehicle	0 %	50 %	0 %	50 %
No. 54	500 Vehicle	0 %	75 %	0 %	25 %
No. 55	500 Vehicle	0 %	100 %	0 %	0 %
No. 56	600 Vehicle	0 %	0 %	0 %	100 %
No. 57	600 Vehicle	0 %	25 %	0 %	75 %
No. 58	600 Vehicle	0 %	50 %	0 %	50 %
No. 59	600 Vehicle	0 %	75 %	0 %	25 %
No. 60	600 Vehicle	0 %	100 %	0 %	0 %
No. 61	100 Vehicle	0 %	0 %	0 %	100 %
No. 62	100 Vehicle	0 %	0 %	25 %	75 %
No. 63	100 Vehicle	0 %	0 %	50 %	50 %
No. 64	100 Vehicle	0 %	0 %	75 %	25 %
No. 65	100 Vehicle	0 %	0 %	100 %	0 %

No. 66	200 Vehicle	0 %	0 %	0 %	100 %
No. 67	200 Vehicle	0 %	0 %	25 %	75 %
No. 68	200 Vehicle	0 %	0 %	50 %	50 %
No. 69	200 Vehicle	0 %	0 %	75 %	25 %
No. 70	200 Vehicle	0 %	0 %	100 %	0 %
No. 71	300 Vehicle	0 %	0 %	0 %	100 %
No. 72	300 Vehicle	0 %	0 %	25 %	75 %
No. 73	300 Vehicle	0 %	0 %	50 %	50 %
No. 74	300 Vehicle	0 %	0 %	75 %	25 %
No. 75	300 Vehicle	0 %	0 %	100 %	0 %
No. 76	400 Vehicle	0 %	0 %	0 %	100 %
No. 77	400 Vehicle	0 %	0 %	25 %	75 %
No. 78	400 Vehicle	0 %	0 %	50 %	50 %
No. 79	400 Vehicle	0 %	0 %	75 %	25 %
No. 80	400 Vehicle	0 %	0 %	100 %	0 %
No. 81	500 Vehicle	0 %	0 %	0 %	100 %
No. 82	500 Vehicle	0 %	0 %	25 %	75 %
No. 83	500 Vehicle	0 %	0 %	50 %	50 %
No. 84	500 Vehicle	0 %	0 %	75 %	25 %
No. 85	500 Vehicle	0 %	0 %	100 %	0 %
No. 86	600 Vehicle	0 %	0 %	0 %	100 %
No. 87	600 Vehicle	0 %	0 %	25 %	75 %
No. 88	600 Vehicle	0 %	0 %	50 %	50 %
No. 89	600 Vehicle	0 %	0 %	75 %	25 %
No. 90	600 Vehicle	0 %	0 %	100 %	0 %

Source: Processed data by author (2024).

4. Results and discussion

4.1 Average Travel Time

An analysis of average travel time reveals compelling insights into the impact of different types of autonomous vehicles (AVs) on travel efficiency. The study examined the effects of varying traffic volumes and penetration rates of cautious, normal, and aggressive AVs on travel time, with the results presented below. As the penetration of AVs increases, there is a consistent reduction in average travel time across all traffic scenarios.

For a traffic volume of 100 vehicles per simulation, the average travel time for human-driven scenarios was 21.35 minutes. With a 25% penetration of cautious AVs, the average travel time decreased to 19.25 minutes, and when the penetration rate reached 100%, it dropped to 13.71 minutes. For normal AVs, the average travel time ranged from 19.27 minutes at 25% penetration to 13.61 minutes at 100%. Aggressive AVs displayed similar trends, with average travel times decreasing from 19.26 minutes at 25% penetration to 13.61 minutes at 100%. These trends are illustrated in Figure 5a.

As traffic volumes increased to 200 vehicles per simulation, the average travel time for human-driven vehicles was 21.33 minutes. With cautious AVs at 25% penetration, the average travel time was 19.51 minutes, while at 100% penetration, it dropped to 13.89 minutes. Normal AVs showed a similar pattern, with average travel times ranging from 19.61 minutes at 25% to 13.84 minutes at 100% penetration. For aggressive AVs, the average travel time varied from 19.52 minutes at 25% penetration to 13.75 minutes at 100%. These results are illustrated in Figure 5b.

In higher traffic volumes of 300 vehicles per simulation, human-driven scenarios exhibited an average travel time of 21.64 minutes. With cautious AV penetration, the time decreased to 14.12 minutes at 100%. Normal AVs yielded similar results, with an average time of 13.83 minutes at 100% penetration. For aggressive AVs, the average travel time decreased from 19.68 minutes at 25% penetration to 13.86 minutes at 100%. This is illustrated in Figure 5c.

The trends continue as traffic volumes increase to 400, 500, and 600 vehicles per simulation. In each scenario, higher penetration rates of all AV types consistently reduce average travel times compared to human-driven scenarios. The notable reduction in travel time, particularly at higher AV penetration rates, underscores the transformative potential of integrating autonomous vehicles into existing traffic systems. These results are illustrated in Figures 5d, 5e, and 5f, demonstrating the potential benefits of autonomous vehicle technology at various traffic volumes. The obtained results align with the outcomes of a study by (Hamadneh & Esztergár-Kiss, 2021), highlighting a notable reduction in travel time and a decline in traditional car usage due to autonomous vehicles (AVs). Analysing AVs' impact on travel behaviour and modal share, both studies underscore the pivotal role of the value of travel time (VOT).

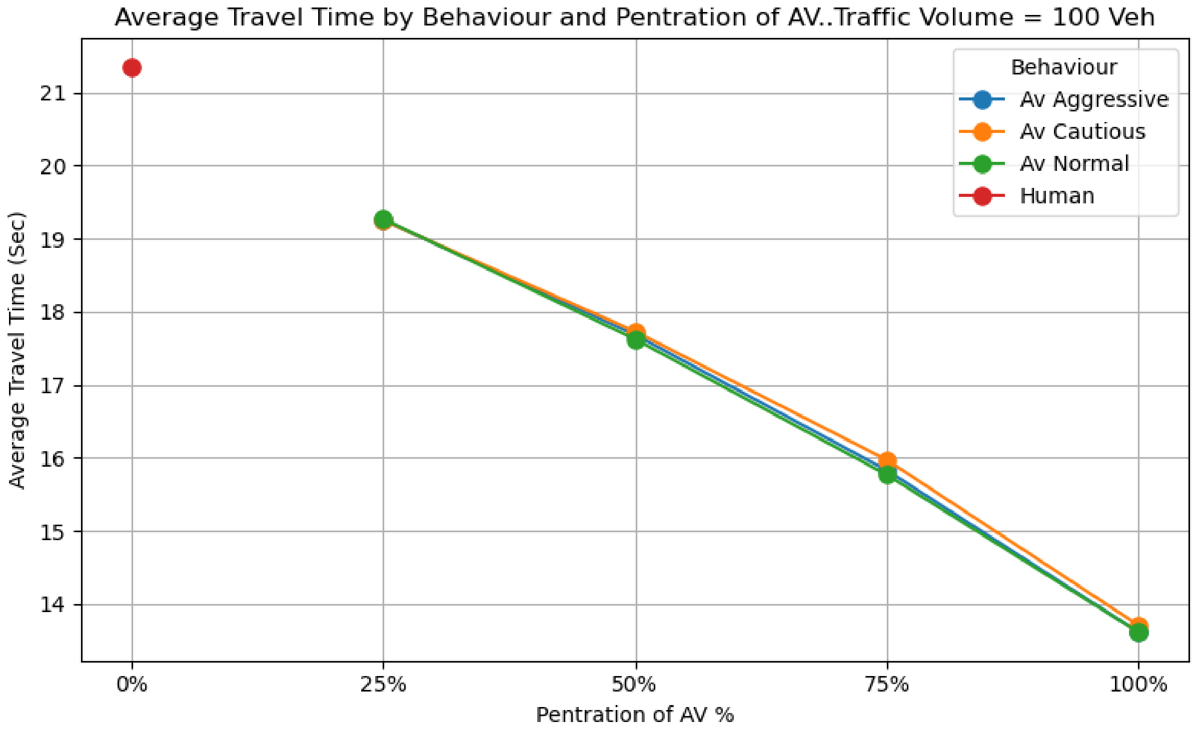

Figure 5a. Average Travel Time by Different Behaviours and Penetrations when Traffic Volume = 100 Vehicle.

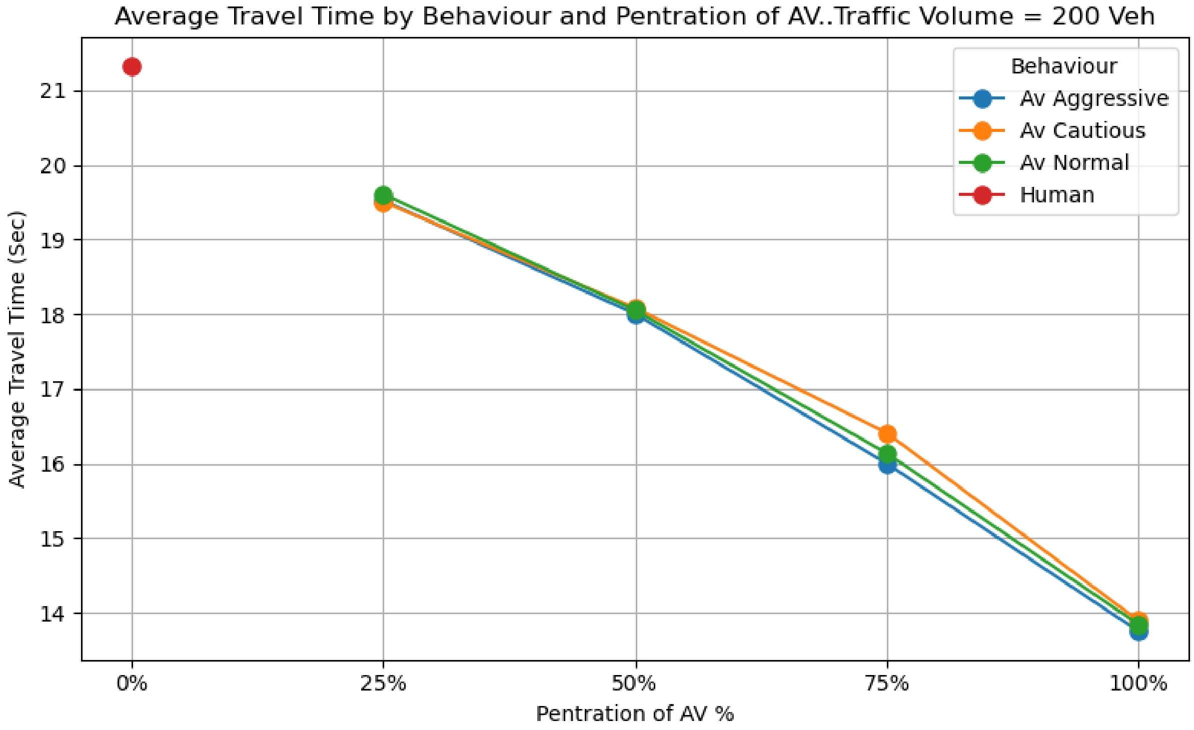

Figure 5b. Average Travel Time by Different Behaviours and Penetrations when Traffic Volume = 200 Vehicle.

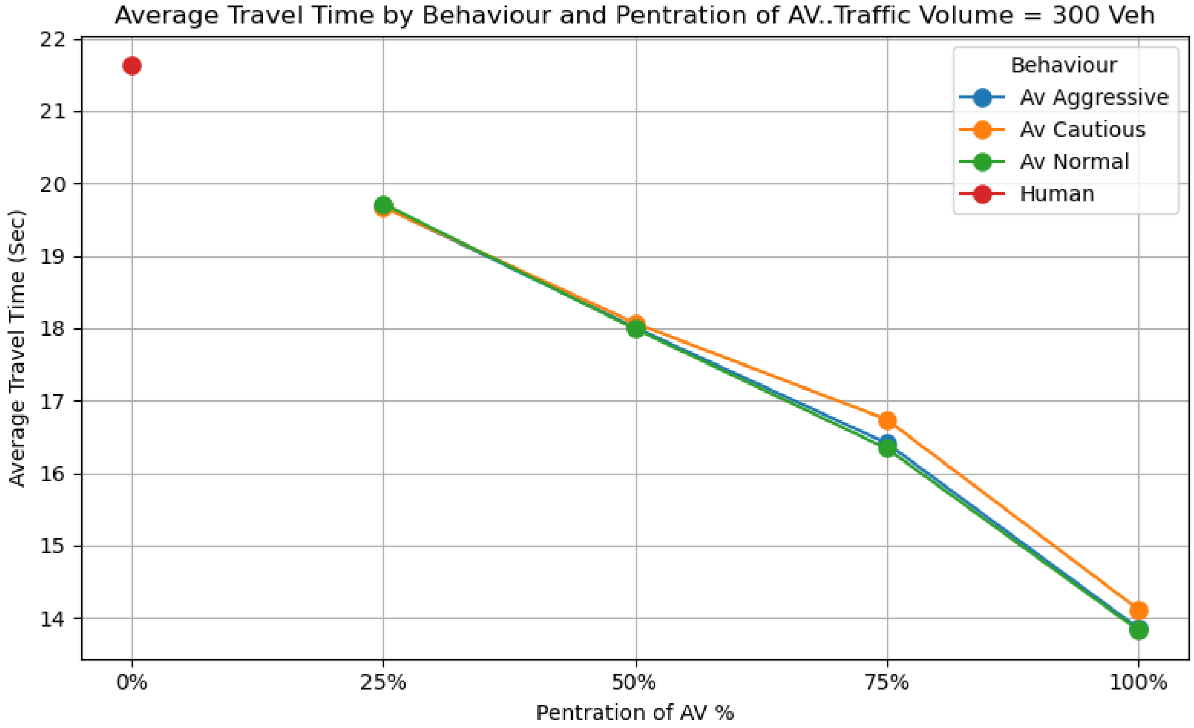

Figure 5c. Average Travel Time by Different Behaviours and Penetrations when Traffic Volume = 300 Vehicle.

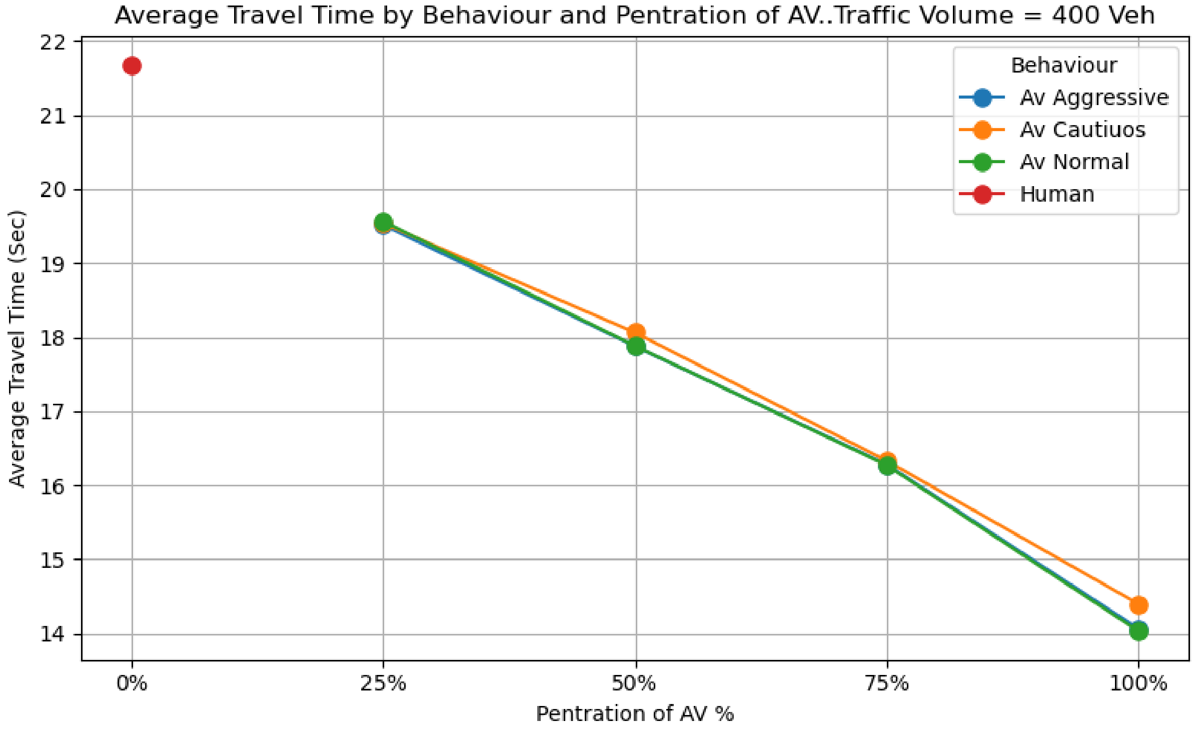

Figure 5d. Average Travel Time by Different Behaviours and Penetrations when Traffic Volume = 400 Vehicle.

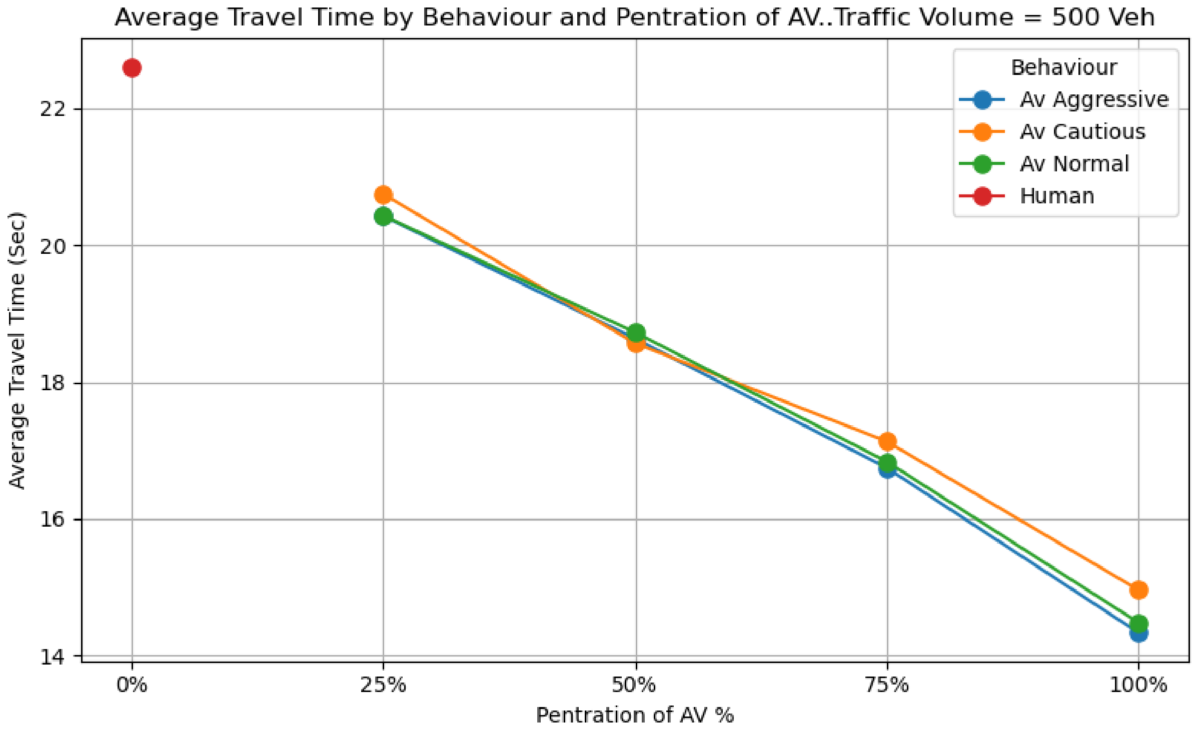

Figure 5e. Average Travel Time by Different Behaviours and Penetrations when Traffic Volume = 500 Vehicle.

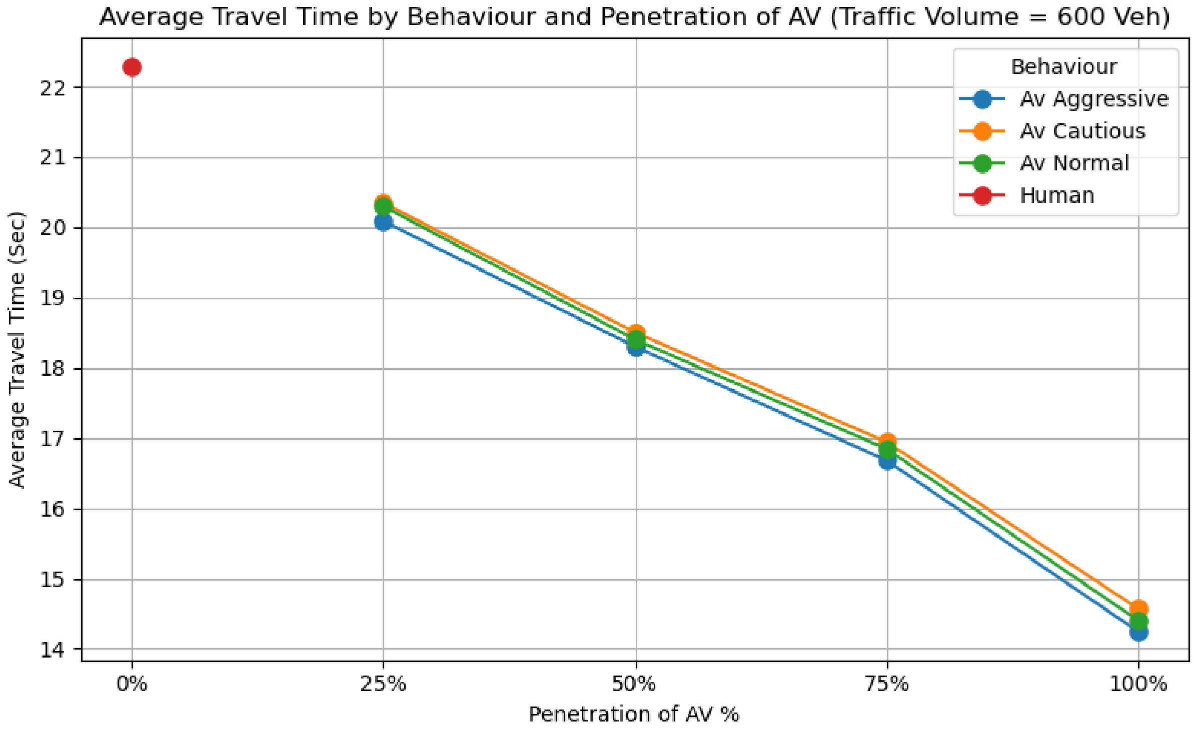

Figure 5f. Average Travel Time by Different Behaviours and Penetrations when Traffic Volume = 600 Vehicle.

4.2 Average Vehicle Emissions and Fuel Consumption

The analysis of average vehicle emissions and fuel consumption reveals favourable outcomes with the integration of autonomous vehicles (AVs) of various types: cautious, normal, and aggressive. The study examined emissions of carbon monoxide (CO), nitrogen oxide (NOX), volatile organic compounds (VOCs), and fuel consumption across different traffic volumes and penetration rates, with results shown in Figure 6(a-f). Across all traffic volumes, higher penetration rates of AVs consistently lead to lower emissions and improved fuel efficiency, with significant benefits at 100% penetration. In scenarios with 100 vehicles, human-driven vehicles produce 41.14 g of CO. Cautious AVs at 25% penetration emit 39.59 g, while at 100%, CO emissions reduce to 36.75 g. Normal AVs exhibit similar patterns, with CO emissions ranging from 39.61 g at 25% penetration to 36.71 g at 100%. Aggressive AVs range from 39.58 g at 25% penetration to 36.71 g at 100%. In scenarios with 200 vehicles, human-driven vehicles produce 83.64 g of CO. At 25% cautious AV penetration, emissions drop to 81.23 g, and at 100% they fall to 74.09 g. Normal AVs range from 81.59 g at 25% to 74.04 g at 100%, while aggressive AVs range from 81.48 g to 73.23 g. With 100 vehicles, human-driven vehicles produce 8.00 g of NOX. Cautious AVs at 25% penetration drop to 7.70 g, and at 100% they fall to 7.15 g. Normal AVs decrease from 7.71 g at 25% to 7.14 g at 100%, with aggressive AVs following similar trends. At 200 vehicles, human-driven vehicles generate 16.27 g of NOX. Cautious AVs at 25% penetration produce 15.80 g, while at 100%, they drop to 14.42 g. Normal AVs range from 15.87 g to 14.41 g at 100%, while aggressive AVs show reductions from 15.85 g to 14.25 g at 100%. In scenarios with 100 vehicles, human-driven vehicles emit 9.53 g of VOCs. Cautious AVs at 25% penetration drop to 9.18 g, with further reduction to 8.52 g at 100%. Normal AVs range from 9.18 g at 25% to 8.51 g at 100%, with similar trends for aggressive AVs. In scenarios with 200 vehicles, human-driven vehicles emit 19.38 g of VOCs. At 25% cautious AV penetration, emissions drop to 18.83 g, and at 100%, they fall to 17.17 g. Normal AVs range from 18.91 g at 25% to 17.16 g at 100%. Aggressive AVs show a similar pattern, from 18.88 g to 16.97 g. With 100 vehicles, human-driven vehicles consume 0.59 L of fuel. Cautious AVs at 25% penetration consume 0.57 L, dropping to 0.53 L at 100%. Normal and aggressive AVs follow similar trends. In scenarios with 200 vehicles, human-driven vehicles consume 1.20 L of fuel. With 25% cautious AV penetration, consumption drops to 1.16 L, while at 100%, it is 1.06 L. Normal AVs show similar patterns, ranging from 1.17 L to 1.06 L, while aggressive AVs exhibit reductions from 1.17 L to 1.05 L at 100% penetration.

As traffic volume increases to 300, 400, 500, and 600 vehicles, these trends persist. Human-driven vehicles consistently produce higher emissions and fuel consumption compared to autonomous vehicles at higher penetration rates. These results suggest that higher penetration rates of AVs, especially aggressive ones, can significantly reduce emissions and fuel consumption, supporting a more environmentally conscious transportation future, as illustrated in Figure 6c-f. The findings are comparable to the outcomes of findings of a study conducted by (Zhao et al., 2022) that explores the positive impact of connected automated vehicles (CAVs) on fuel consumption and traffic emissions. It reveals that CAVs consistently reduce both aspects, with a higher penetration rate leading to more significant benefits. The study particularly emphasizes a remarkable 32% reduction in fuel consumption and traffic emissions at signalized intersections with 100% CAV penetration. Leveraging car-following models (IDM, ACC, CACC) and the VT-micro model for precise measurements, the research underscores the environmental advantages of CAVs across diverse traffic scenarios.

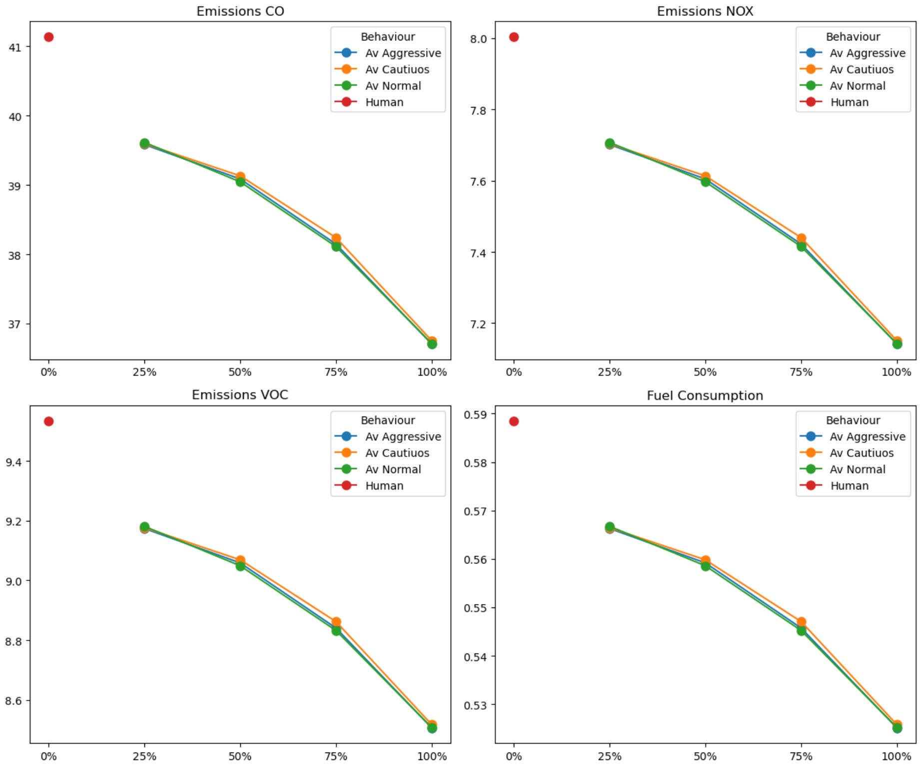

Figure 6a. Emissions and Fuel Consumption by Different Behaviours and Penetrations when Traffic Volume = 100 Vehicle.

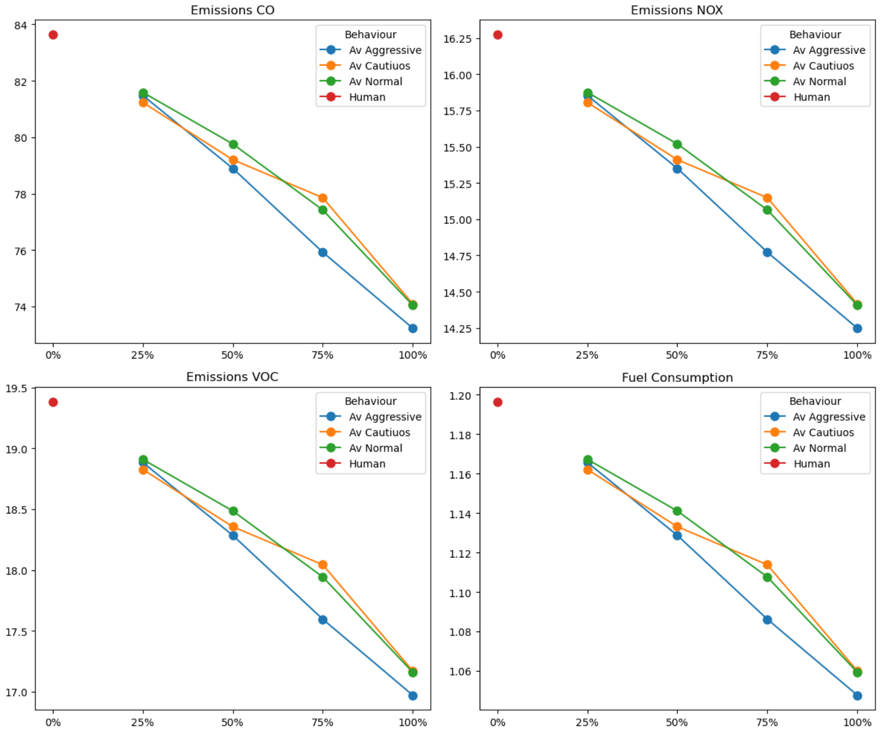

Figure 6b. Emissions and Fuel Consumption by Different Behaviours and Penetrations when Traffic Volume = 200 Vehicle.

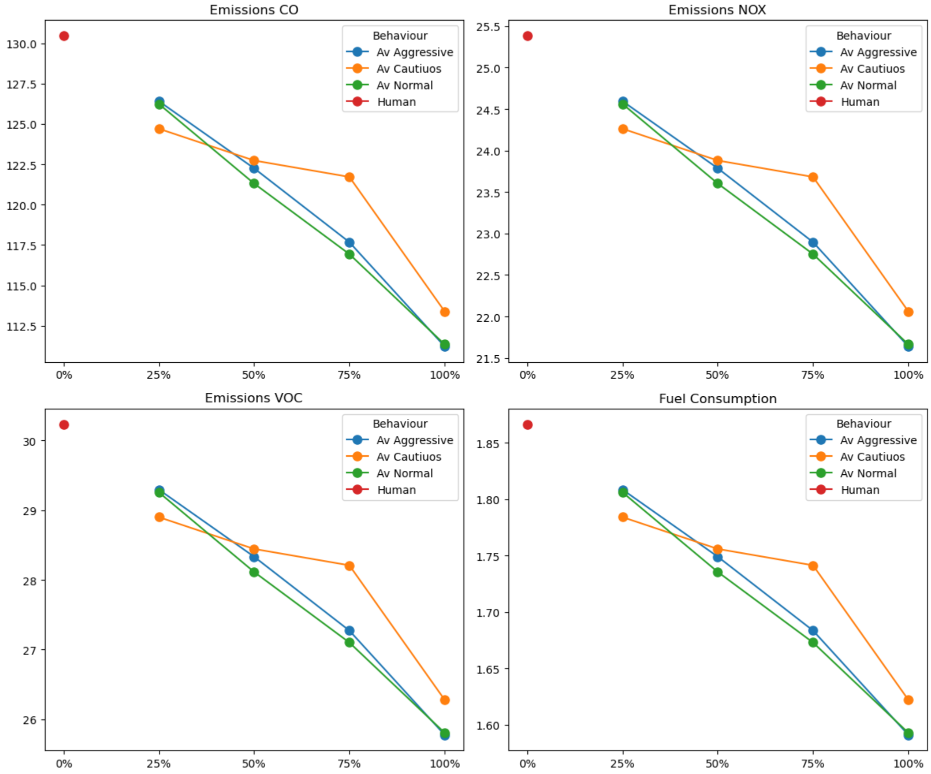

Figure 6c. Emissions and Fuel Consumption by Different Behaviours and Penetrations when Traffic Volume = 300 Vehicle.

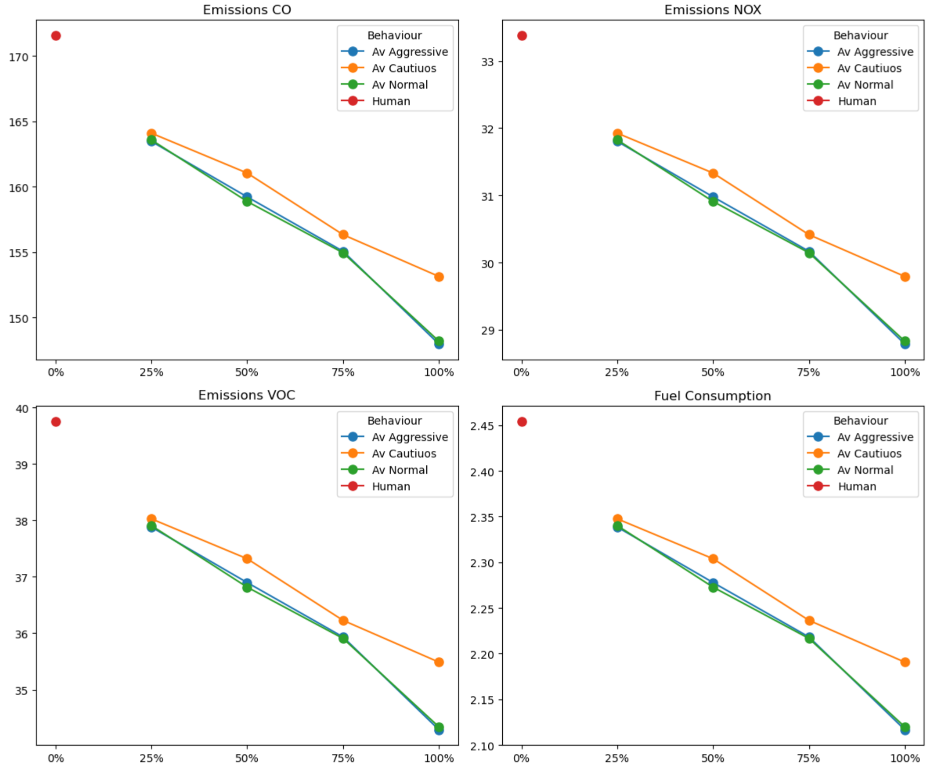

Figure 6d. Emissions and Fuel Consumption by Different Behaviours and Penetrations when Traffic Volume = 400 Vehicle.

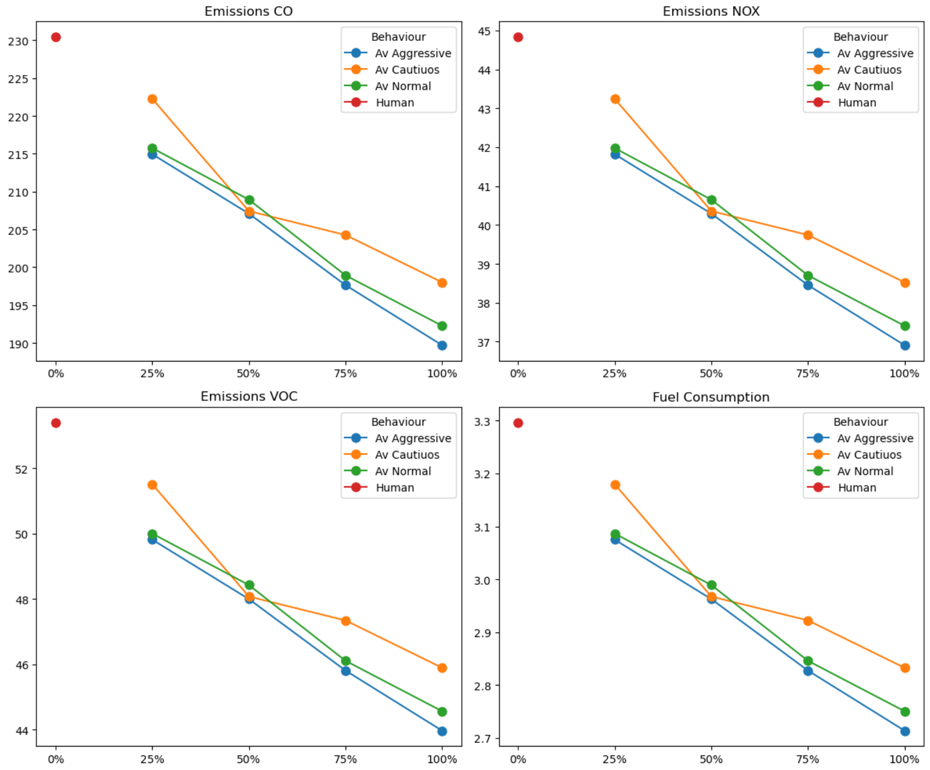

Figure 6e. Emissions and Fuel Consumption by Different Behaviours and Penetrations when Traffic Volume = 500 Vehicle.

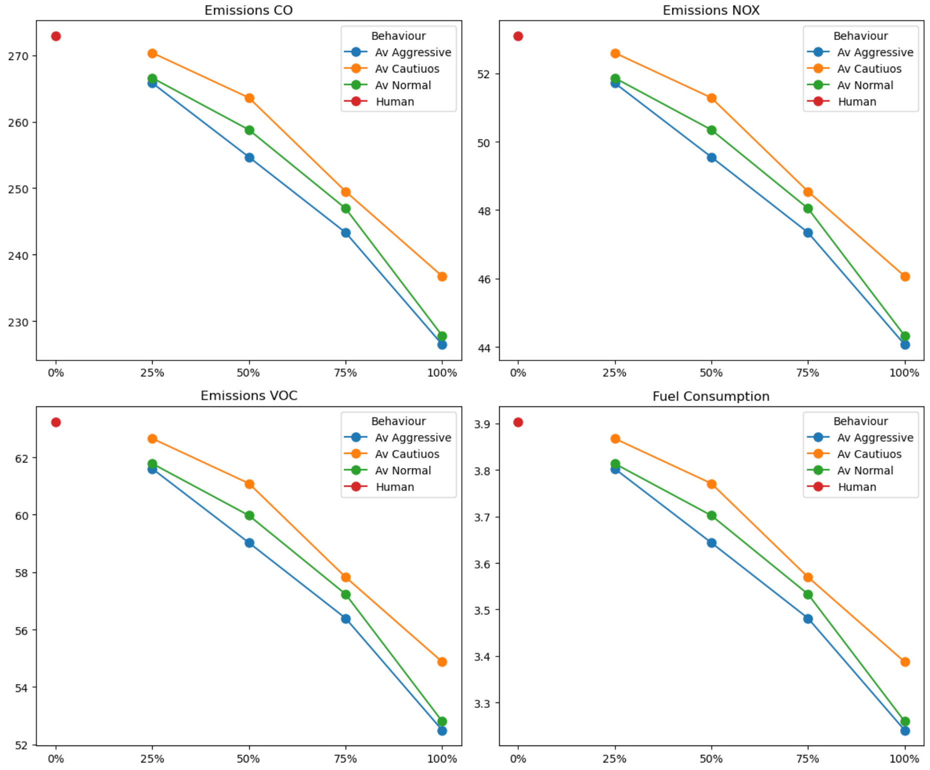

Figure 6f. Emissions and Fuel Consumption by Different Behaviours and Penetrations when Traffic Volume = 600 Vehicle.

5. Conclusion

This study's comprehensive analysis of traffic dynamics at a Kirkuk, Iraq, roundabout examined the impact of increasing traffic volume and different types of autonomous vehicles (AVs) on travel time, emissions, and fuel consumption. The study evaluated the effects of integrating cautious, normal, and aggressive AVs into traffic scenarios. The results reveal that as AV penetration rates increase, there is a consistent reduction in travel time, emissions, and fuel consumption, with aggressive AVs demonstrating the most significant benefits.

- Travel Time: Aggressive AVs at 100% penetration consistently achieve the shortest travel times, ranging from 13.61 minutes with 100 vehicles to 14.24 minutes with 600 vehicles. Cautious and normal AVs also show significant reductions in travel time compared to human-driven scenarios. For example, with 100 vehicles, cautious AVs at 100% penetration have a travel time of 13.71 minutes, while normal AVs have 13.61 minutes.
- Emissions: Emissions of carbon monoxide (CO), nitrogen oxide (NOX), and volatile organic compounds (VOCs) all decrease as AV penetration rates increase. For example, with 100% penetration of aggressive AVs, CO emissions range from 36.75 g with 100 vehicles to 226.50 g with 600 vehicles. Cautious and normal AVs also show a similar trend, indicating their environmental benefits.
- Fuel Consumption: The study shows that 100% penetration of aggressive AVs leads to lower fuel consumption, ranging from 0.53 L with 100 vehicles to 3.24 L with 600 vehicles. Cautious and normal AVs also follow this trend, with significant reductions compared to human-driven scenarios.

These outcomes highlight the benefits of integrating AVs, particularly aggressive ones, in reducing travel time, emissions, and fuel consumption. The study suggests that higher penetration rates of AVs, regardless of behaviour type, can support a more sustainable and efficient transportation system.

To ensure the generalizability of these findings, future studies should consider a broader range of traffic scenarios and the specific characteristics of different intersections. Exploring varying geometries, traffic conditions, and cultural contexts can provide a more robust understanding of how these trends apply to diverse settings. Additionally, incorporating a wider array of autonomous vehicle (AV) behaviours and penetration rates can offer further insights into their impact on traffic dynamics. This approach helps to understand better the effectiveness and potential challenges of integrating autonomous vehicles into existing traffic systems.

6. Limitations

This study's limitations stem from the inherent constraints of simulation-based approaches, which rely on assumptions and simplifications that might not fully capture the complexities of real-world traffic scenarios. The focus on a specific roundabout in Kirkuk, Iraq, reduces the study's generalizability, as the results might not apply to different intersections, urban contexts, or regional conditions. Additionally, the simulation uses a predefined penetration rate for autonomous vehicles (AVs) across cautious, normal, and aggressive behaviours. This approach may not reflect the full spectrum of real-world variations in AV adoption and behaviour. The study's emphasis on traffic volume increase could also limit the broader understanding of other significant factors that influence traffic dynamics. For instance, road conditions, weather variations, real-time driver behaviour, and traffic management practices could play critical roles in shaping traffic patterns.

Another limitation is the focus on a limited range of traffic volumes and behaviours, which might not represent the full potential of autonomous vehicles in various urban settings. Future research could explore a wider array of AV behaviours, different traffic conditions, and other significant parameters to obtain a more comprehensive understanding of the effects of AV integration.

Researchers' Contribution Rate Statement

The authors' contribution rates in the study are equal.

Conflict of Interest Statement, if any

There is no conflict of interest with any institution or person within the scope of the study.

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