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Assessing Traffic Performance: Comparative Study of Human and Automated HGVs in Urban Intersections and Highway Segments

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Heavy goods vehicles (HGVs), automated heavy goods vehicles (HGVs), traffic dynamics, highway traffic, emissions analysis, fuel consumption, PTV VISSIM model

Abstract

This study conducts a comparative analysis of traffic dynamics at urban signalized intersections and on highways, incorporating both human-operated and automated heavy goods vehicles (HGVs) using the PTV VISSIM simulation model. It examines the impacts of automated driving technologies on critical traffic performance metrics such as queue length, travel time, vehicle delay, emissions, and fuel consumption. Initial findings indicate that automation in HGVs enhances traffic flow, particularly by reducing queue lengths and vehicle delays. However, varying levels of automation from cautious to aggressive reveal complex trade-offs between operational efficiency and environmental impacts. On highways, automated HGVs demonstrate superior performance by reducing travel times and delays while increasing throughput compared to human-driven HGVs. These results underscore the operational benefits of automated HGVs under diverse traffic conditions and highlight their significant implications for transportation planning and policy-making. This research contributes valuable insights into the integration of automated technologies in transportation systems, facilitating informed decision-making for stakeholders considering the adoption of these advancements in the current infrastructure.

1. Introduction

The integration of automated technologies into heavy goods vehicle (HGV) operations is supposed to bring a transformation in the current scenario of transportation systems [1]-[5]. Autonomous vehicles (AVs) represent one of the most topical areas where developing urban congestion and the rising importance of environmental sustainability intersect in significant ways [6]-[12]. These technologies are not just making vehicles operate differently but are transforming the very strategic frame of transportation planning and policy development [13]-[18].

This paper describes a wide analysis of traffic dynamics, with dual focus on the dynamics at urban signalized intersections and highway environments, which are very critical nodes and links in urban transport networks. In this investigation, the advanced capabilities of the PTV VISSIM model are extensively used in making simulations to delve deep into this comparative human-operated performance and the performance of HGVs in very varied automated configurations across a traffic scenario spectrum. In that sense, this study simulates real conditions to provide a detailed examination of how automated driving technologies could interact with traditional traffic systems. To describe operational differences in the performance of queue length, travel time, vehicle delay, emissions, and fuel consumption between human-driven and autonomous HGVs, key performance metrics are analyzed. Thus, the paper focuses more specifically on three attributes of AV HGVs which are considered to define them: Cautious, Normal, and Aggressive. Each of these attributes is tested for its effects in traffic flow, emission levels, and systems efficiency at an incremental level.

The addition of empirical data and simulation results means that this paper will provide a conceptual framework to bridge the gap between theoretical knowledge and practical application, hence building and giving value to new knowledge in the literature about automated transportation. This will in one way, or another provide valuable information for policy developers, transportation planners, and stakeholders in making informed decisions on the deployment of AV technologies. In this regard, this paper points not at the changing potential that AV HGVs might hold upon the performance of transport systems; what is more, it pinpoints the very fine interplay of technological solutions and traffic management strategies, where policy frameworks need to be flexible and informed to fully allow for the automation benefits in a changing urban landscape.

2. Literature Review

A summary of some of the existing studies on the impact of Automated HGVs on travel behavior and transportation systems is briefly presented in Table 1. These studies have provided important insights into what travel patterns, mode choice, and the value of travel time savings are implied in the adoption of Automated HGVs. While such research has significantly contributed to our understanding of the overall effects of Automated HGVs, there remains a gap in the literature concerning the examination of various Automated HGV behaviors and their individual impacts on travel times and vehicle arrivals, particularly regarding metrics such as queue length, travel time, vehicle delay, emissions, and fuel consumption. This research seeks to address this gap by focusing on the behavioral dynamics of Automated HGVs, specifically exploring the concepts of AV Cautious, AV Normal, and AV Aggressive driving behaviors.

It is noteworthy that studies specifically analyzing the nuanced behaviors of Automated HGVs and their discrete impacts within complex traffic systems are scant. This scarcity highlights a critical area of research that has yet to be thoroughly explored, emphasizing the value and timeliness of this work. By delving into the distinct behavioral dynamics of Automated HGVs, this study not only fills an important gap but also extends the existing body of knowledge, providing detailed insights that could guide future technological implementations and policy developments in the field of automated transportation. Our research, therefore, plays a pivotal role in enriching the discourse and understanding of how automated technologies can be optimized to improve the efficiency and sustainability of transportation systems worldwide.

Table 1 *Summary of studies investigating the impact of autonomous HGVs on transportation systems*

Reference	Year	Objective of The Study	Methodology/Tools Used	Key Findings
[19]	2019	Develop a heavy-goods conveying device capable of autonomous omni-directional travel without turning the wheels.	Device design	1. Creation of a heavy-duty conveying device enabling 360-degree rotation and diagonal movement for uninterrupted heavy material transport. 2. Achieved autonomous omni-directional travel without wheel turning, allowing direction

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				switching in all four directions without changing wheel angles.
[20]	2022	Explore new exterior design options to enhance the efficiency of fully autonomous heavy-duty vehicles.	Analysis of design modifications.	1. New design options, such as aerodynamic superstructures and increased cargo space, aimed at improving safety, energy consumption, and addressing driver shortage in autonomous heavy-duty vehicles. 2. Reducing trailer compartment height on empty runs demonstrated potential to lower fuel consumption. 3. EU regulations impose restrictions on implementing new exterior design options for heavy-duty trucks, particularly in Germany, limiting frontal area reduction.
[21]	2022	Develop telematic automated system for weight control of heavy vehicles.	Mathematical modeling, telematic system development.	1. Increased Road transport efficiency and performance indicators. TASWC HGV improves road transport efficiency, operational indicators, and enhances road transport efficiency, safety, and user comfort. Focus on improving efficiency of road transport through telematic systems. Address overweight cargo issues in road transportation for better safety. Shortcomings of existing weight control system for heavy vehicles, highlighting inefficiency in relation to road infrastructure.
[22]	2023	Development of Programmed Autonomous Electric Heavy Vehicle: An Application of IoT.	IoT integrated obstacle detection system. Sensors: LiDAR, ultrasonic, intelligent camera.	1. Improved safety in on-road and off-road construction environments. 2. Focus on safety improvement in construction on-road and off-road. 3. Utilization of LiDAR, ultrasonic, and intelligent-camera sensors.

3. Methodology

3.1 Study Location & Data Collection

For this study, a random intersection has been selected in Kirkuk, Iraq, to serve as the primary simulation location for urban signalized intersections as shown in Fig. 1. Kirkuk, situated in northern Iraq, represents a typical urban setting with diverse traffic patterns and infrastructure characteristics.

Fig. 1 *Geographical depiction of the signalized traffic intersection in Kirkuk, Iraq*

Additionally, data collection for highway simulations was conducted along the Kirkuk-Sulaymaniyah Highway as shown in Fig. 2, a major arterial route connecting Kirkuk with Sulaymaniyah.

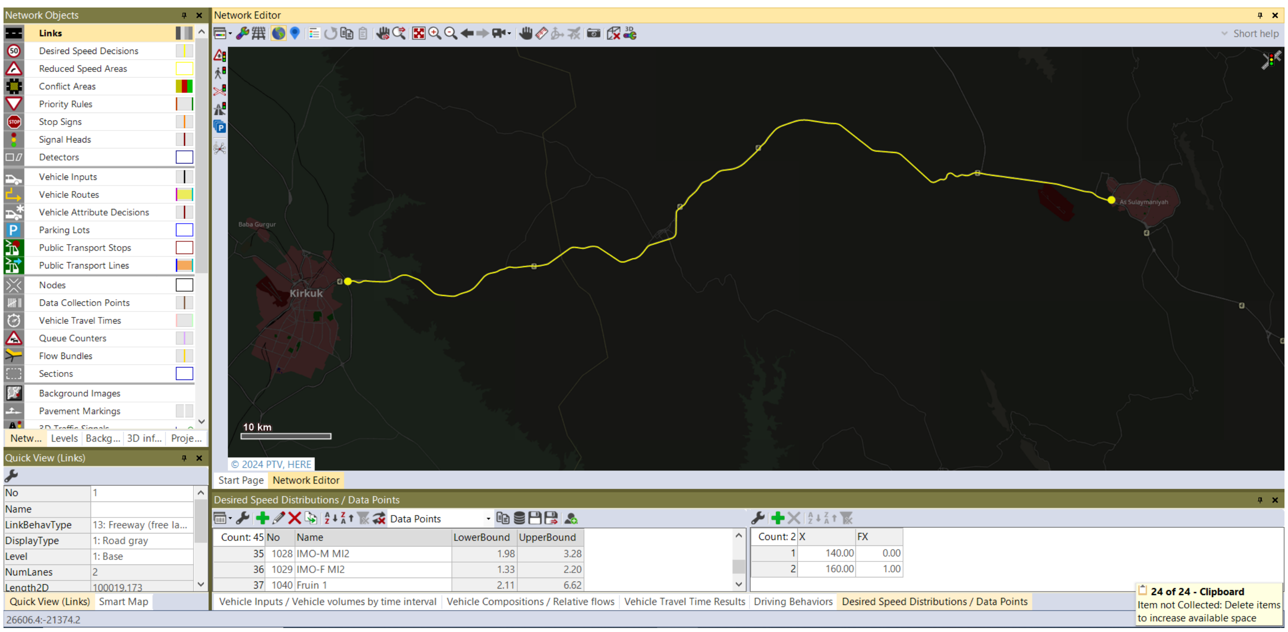

Fig. 2 *View of highway segment between Kirkuk and Sulaymaniyah in PTV VISSIM model*

The examined traffic volumes for the intersection were selected randomly with 3600 sec simulation period. Starting with a baseline volume of 1000 HGVs, additional volumes of 1100 and 1200 were chosen, as indicated in Table 2. This random selection process aimed to capture a range of traffic conditions and provide a comprehensive analysis of the intersection's performance under varying levels of vehicle density. By examining these different traffic volumes, the study aims to elucidate the influence of Automated HGV flow on intersection dynamics, including queue length, travel time, and vehicle delay, thereby informing strategies for efficient traffic management and urban planning. Additionally, the signal cycle time was set to be 96, as shown in Fig. 3, to further explore its impact on intersection efficiency and overall traffic flow.

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Table 2 *Summary of examined traffic volumes for the intersection*

Total Traffic Volume	Bound	HGVs Count	Movement Ratio		
			Right	Straight	Left
1000 HGV	North	300	.333	.333	.333
	East	200	.333	.333	.333
	South	300	.333	.333	.333
	West	200	.333	.333	.333
1100 HGV	North	300	.333	.333	.333
	East	250	.333	.333	.333
	South	300	.333	.333	.333
	West	250	.333	.333	.333
1200 HGV	North	300	.333	.333	.333
	East	300	.333	.333	.333
	South	300	.333	.333	.333
	West	300	.333	.333	.333

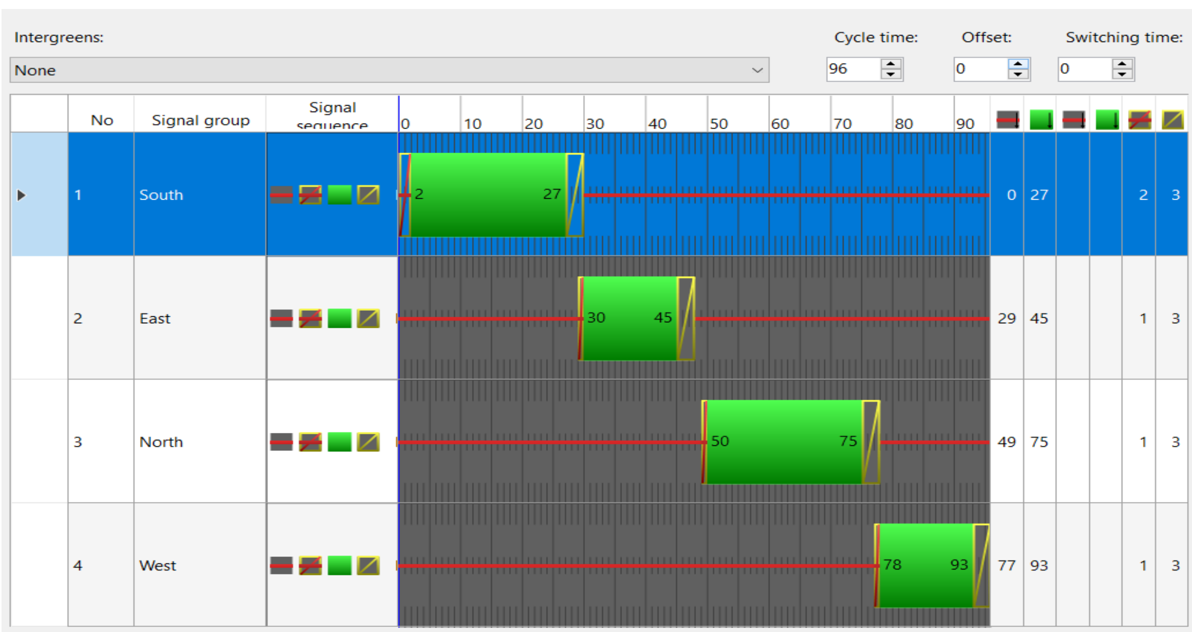

Fig. 3 *Traffic signal configuration in PTV VISSIM model*

The traffic volume for the highway segment was structured according to the scenarios outlined in Table 3. Each scenario represented a different level of traffic intensity, representing only HGVs; a parallel scenario included Automated HGVs to test their effect with the simulation period of 5400 s.

Table 3 *Summary of examined traffic volume for the highway segment*

Scenario	Traffic Volume	Vehicle Composition
1	1000 HGV	Conventional HGV, AV HGV
2	1100 HGV	Conventional HGV, AV HGV
3	1200 HGV	Conventional HGV, AV HGV

3.2 Experimental Design

3.2.1 PTV VISSIM

PTV VISSIM software is commonly used for microscopic simulation in the field of transportation engineering and research, including our study. It is therefore a very robust model for the simulation of complex traffic scenarios and fluctuating traffic flows within our study of Automated Heavy Goods Vehicles. The very high flexibility of PTV VISSIM in this regard is such that it would allow the interface to be customized for personalized simulation of the roadway and traffic conditions with relevant vehicle behavior, in a manner commensurate with our study. With well-documented vehicle movement algorithms, PTV VISSIM accurately reproduces vehicle interactions, lane changes, and intersection maneuvers, which are very important for the understanding of the effect of Automated HGV behavior on traffic dynamics. Moreover, its advanced model features facilitate the simulation of traffic signal control, vehicle routing, and dynamic assignment, providing comprehensive analysis of traffic operations and performance under varying scenarios. With its user-friendly interface and powerful simulation capabilities.

3.2.2 Car Following Model Parameters

Human drivers typically adhere to traditional basic car-following models, which are sensitive to the traffic state and result in various reaction times. In contrast, AVs display a spectrum of car-following behaviors, spanning from cautious to aggressive, impacting their capacity to maintain appropriate following distances and respond to dynamic traffic conditions. The specific parameters governing these behaviors are detailed in Table 4.

3.2.3 Lane Change Model Parameters

In the study, lane change model parameters are meticulously adjusted to reflect the diverse driving behaviors exhibited by AV HGVs and human drivers, aiming to closely mirror real-world driving scenarios. While advanced merging capabilities are universally enabled, cooperative lane change functionality is exclusively activated for AV HGVs, highlighting a significant disparity in technological integration between AVs and human-operated vehicles. Notably, the safety distance reduction factor varies significantly across categories: AV cautious mode maintains a conservative 1.00 meter, AV normal mode reduces it to 0.60 meters, AV aggressive mode further reduces it to 0.75 meters, while human drivers adhere to a 0.60-meter safety distance. Minimum clearance (front/rear) parameters also exhibit distinct values; set at 1.00 meter for AV cautious mode to prioritize safety and reduced to 0.50 meters for other modes. In addition, the cooperative braking maximum deceleration differs according to the following values: -2.50 m/s^2 for AV cautious, -3.00 m/s^2 for AV normal, -6.00 m/s^2 for AV aggressive, -3.00 m/s^2 for human drivers, which conveys that the handling of dramatic decelerations of the traffic flow is different.

Table 4 *Car following model parameters for different driving behavior*

Wiedemann 99 following model parameters	HGV AV Cautious	HGV AV Normal	HGV AV Aggressive	Human HGV
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

All these, as presented in Table 5, constitute an important part of the input parameters to simulate the response of different driving modes under a variety of traffic conditions for better studying the AV HGV dynamics better in mixed-traffic scenarios.

Table 5 *Lane change model parameters for different driving behavior*

Parameter's	HGV AV Cautious	HGV AV Normal	HGV AV Aggressive	Human HGV
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/s²	-3.00 m/s²	-6.00 m/s²	-3.00 m/s²

3.2.4 HGV Distributions

The weight and power distribution in the simulation have been set very carefully to represent the most popular HGVs, with all features intact, as presented in Fig. 4. These settings have been done through the PTV VISSIM software in such a manner that they represent, to a high degree of accuracy, the typical weight distribution and power characteristics that are common in the real world among HGVs. Set adherence in the industry and common HGV settings makes for realistic vehicle behavior settings within the simulation environment. Overall, the approach augments the fidelity of the simulation results and supports the accurate representation of traffic dynamics, which can allow researchers to find valuable findings in the behavior of HGVs under different traffic conditions.

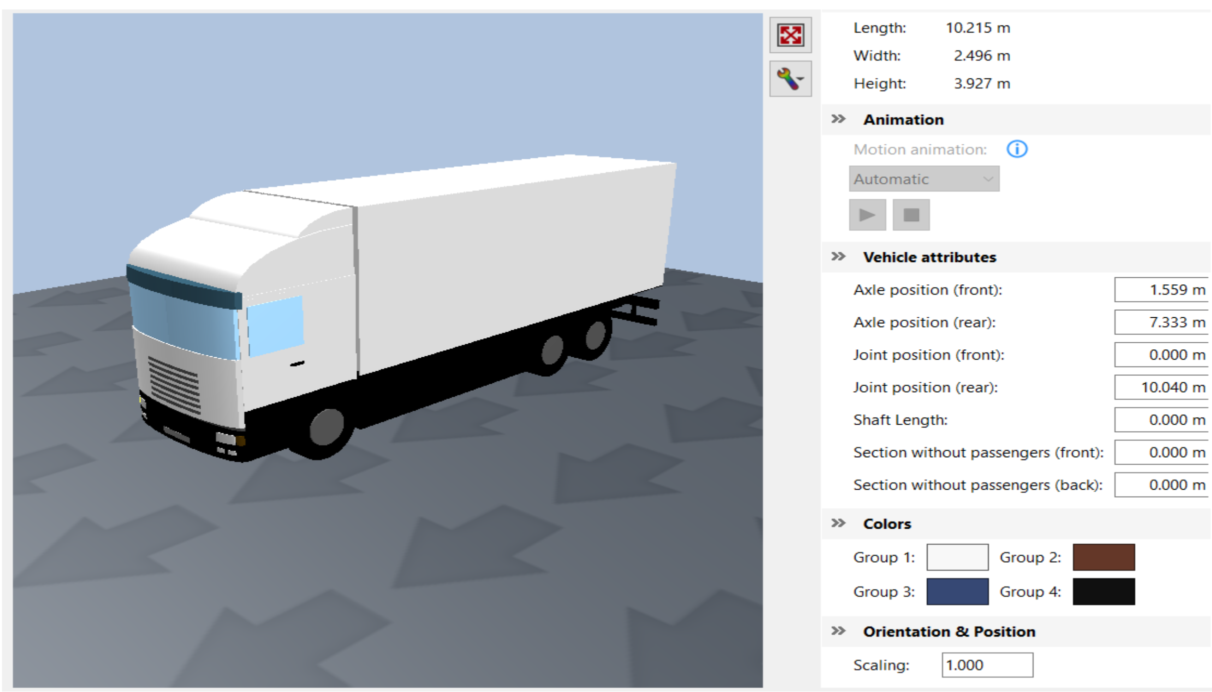

Fig. 4 *3D model of HGVs in PTV VISSIM*

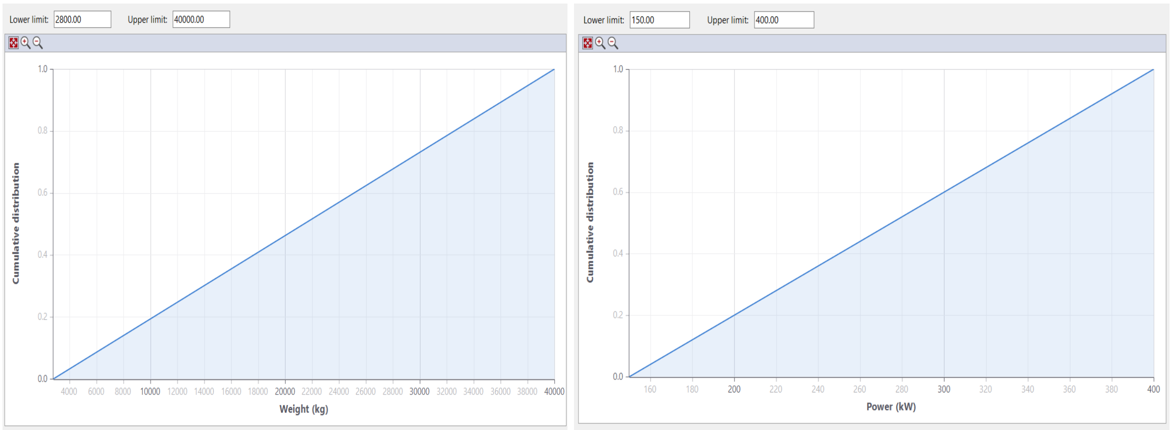

Fig. 5 *Weight and power distribution of HGVs in PTV VISSIM*

Note that the speed distributions of both conventional and AV HGVs have been properly set in the simulation to reflect the conditions of the real world. The speeds inside the intersection were taken to consider all the speeds in the range from 40 km/h to 45 km/h, as seen in Fig. 6. Such ranges were considered as being representative of the typical speeds found in urban traffic. This made it possible to ensure that the vehicle behavior in the test environment is as close to reality as possible. Because the speed distributions are realistic, appropriate speed values will be realized, which are important in making inferences on the nature of variability in the vehicle speeds and the role in traffic flow dynamics, further making the intersection performance analysis credible and yielding real results on the influence of AV technology on HGV operations.

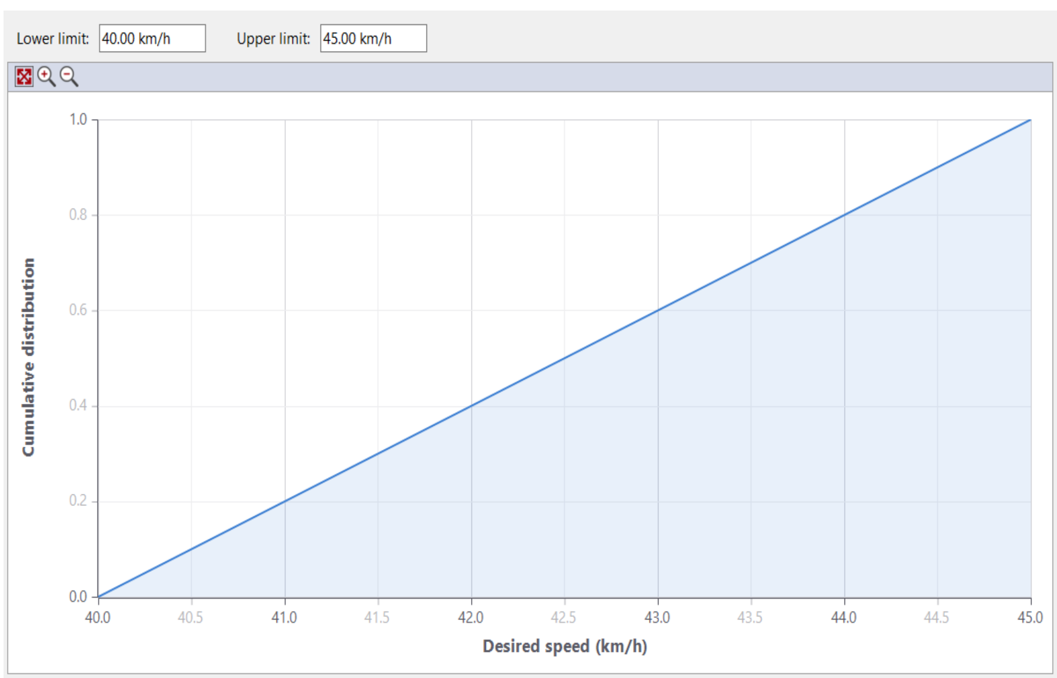

Fig. 6 *Speed distribution of HGVs in the intersection*

The speed distributions for this highway segment are designed to mimic the characters of the conventional and the AV HGVs. Fig. 7 shows the systematic speeds that have been chosen in the range of speeds represented in a typical highway scenario between 85 km/h and 120 km/h. As can be observed in the simulation parameters, this selection is characteristic of a large proportion of the selection of speeds that can be experienced on highways and is likely to allowing for a comprehensive examination of HGV behavior and interaction with other vehicles. By accurately modeling speed distributions across the highway segment, the simulation endeavors to provide insights into traffic flow dynamics, travel times, and overall transport efficiency under varying speed conditions.

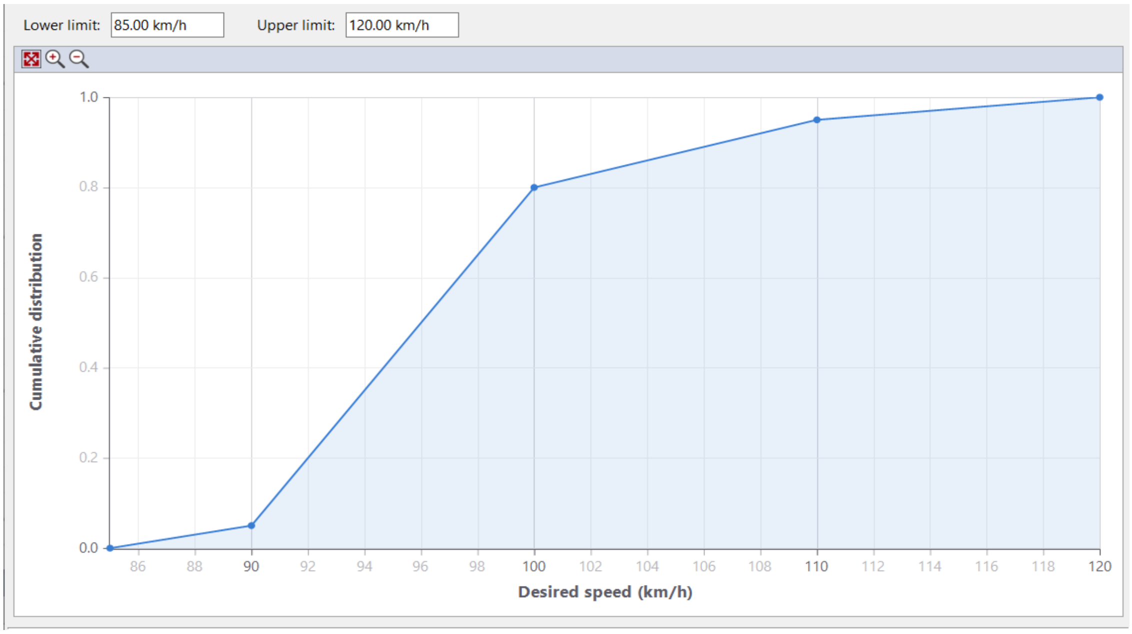

Fig. 7 *Speed distribution of HGVs in the highway segment*

3.2.5 Experimental Scenarios

The experimental scenarios implemented in this study constitute a comprehensive overview of the traffic dynamics and performance assessment under varying conditions within the Intersection and Highway. Various scenarios have been designed by careful simulation modeling to reflect a spectrum of traffic volume and the behavioral dynamics of automated heavy goods vehicles. The baseline volume of traffic in HGVs is 1,000, increased to 1,100 and 1,200 HGVs, as depicted in Table 6, giving full details of the traffic flow dynamics for different vehicle densities.

Table 6 *Overview of experimental scenarios*

Intersection Scenarios		Highway Scenarios	
Traffic Volume	Scenario	Traffic Volume	Scenario
1000 HGV	Scenario 1 (100% Human HGV)	1000 HGV	Scenario 11 (100% Human HGV)
	Scenario 2 (100% AV Cautious HGV)		Scenario 12 (100% AV Cautious HGV)
	Scenario 3 (100% AV Normal HGV)		Scenario 13 (100% AV Normal HGV)
	Scenario 4 (100% AV Aggressive HGV)		Scenario 14 (100% AV Aggressive HGV)
1100 HGV	Scenario 5 (100% AV Cautious HGV)	1100 HGV	Scenario 15 (100% AV Cautious HGV)
	Scenario 6 (100% AV Normal HGV)		Scenario 16 (100% AV Normal HGV)
	Scenario 7 (100% AV Aggressive HGV)		Scenario 17 (100% AV Aggressive HGV)
1200 HGV	Scenario 8 (100% AV Cautious HGV)	1200 HGV	Scenario 18 (100% AV Cautious HGV)
	Scenario 9 (100% AV Normal HGV)		Scenario 19 (100% AV Normal HGV)
	Scenario 10 (100% AV Aggressive HGV)		Scenario 20 (100% AV Aggressive HGV)

4. Results and Discussion

4.1 Intersection Metrics Result Analysis

4.1.1 Average Queue Length Results

The analysis of queue lengths for different traffic volumes and driving scenarios for HGV reveals distinct patterns across human-driven and autonomous vehicle (AV) modes. With a base of 1000 HGV vehicles, human-driven HGVs exhibited the longest queue with an average length of approximately 21.1 meters. The introduction of autonomous technology in HGVs showed a significant reduction in queue lengths; cautious AVs reduced the length to about 19.1 meters, normal AVs to around 17.0 meters, and aggressive AVs to approximately 16.0 meters, indicating more efficient queue management.

As traffic volume increased, the impact of autonomous driving became more pronounced. With 1100 HGVs, the queue length for cautious AVs rose to about 24.3 meters, while normal and aggressive AV modes exhibited shorter queues of approximately 18.7 meters and 17.0 meters respectively. At the highest tested volume of 1200 HGV vehicles, cautious AVs experienced a queue length nearing 29.3 meters. However, normal, and aggressive AV modes maintained relatively stable and shorter queues, at roughly 21.9 meters and 21.1 meters respectively. These results are illustrated in Fig. 8.

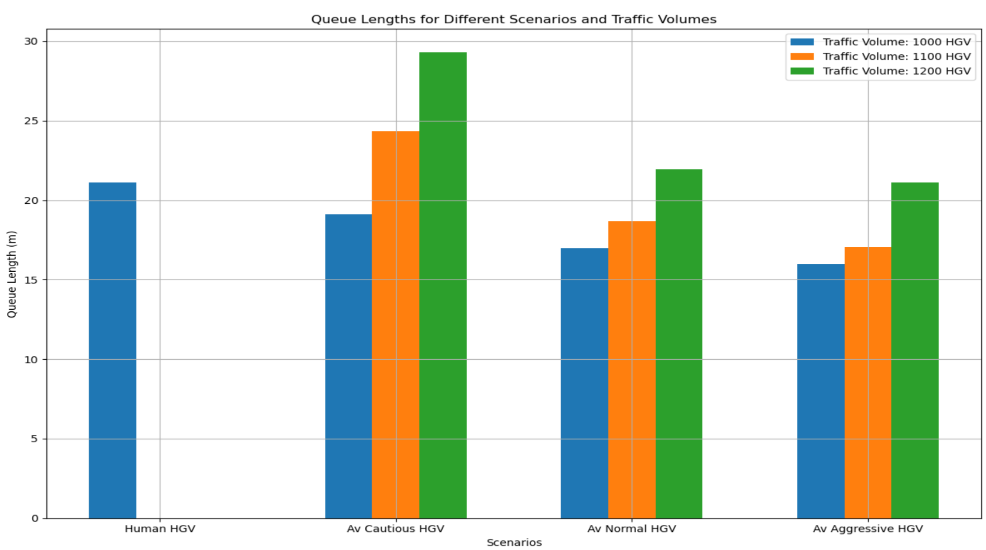

Fig. 8 *Comparative analysis of queue lengths by driving mode and traffic volume for automated HGVs*

In analyzing queue lengths under different traffic conditions, it is notable how automated HGVs compare to human-driven HGVs at various volumes. For human-driven HGVs, the queue length stood at approximately 21.1 meters with 1000 vehicles. In the case of aggressive automated HGVs, this queue length was replicated with 1200 vehicles, demonstrating that aggressive automated HGVs could handle an increase of 200 vehicles while maintaining the queue length efficiency seen in human-driven settings at lower volumes. Similarly, normal automated HGVs showed a queue length of approximately 16.9 meters when it was about 1000 vehicles. The same length was exhibited in the case of 1100 vehicles, which means that with an increase of 100 vehicles, normal automated HGVs were able to show a queue length already exhibited at a lower volume. This is a very efficient characteristic of normal automated HGV modes in managing rising traffic in an effective manner.

For cautious automated HGVs, the lengths of queues went higher as the numbers of vehicles were increased, they managed to maintain a shorter queue compared to human-operated scenarios at corresponding increases in vehicle numbers. As an example, the cautious automated HGVs had an approximate queue length of 19.1 meters under traffic of 1000 vehicles and a further length increase to 24.3 meters under 1100 vehicles. At 1200 vehicles, the length went up to about 29.3 meters, which is a reflection of a more conservative approach to coping with more significant amounts of traffic and, therefore, resulting in a longer queue compared to settings of more assertive automated HGVs.

These findings highlight the potential of automated HGVs, particularly in aggressive and normal settings, to efficiently manage higher traffic volumes by maintaining or slightly increasing queue lengths under heightened traffic loads, thereby outperforming human-driven HGVs in similar conditions. This suggests that adopting automated HGVs could lead to more effective traffic flow and reduced congestion, especially as traffic volumes increase.

4.1.2 Average Travel Time Results

At a traffic volume of 1000 vehicles, human-driven HGVs recorded an average travel time of approximately 55.89 seconds as illustrated in Fig. 9. Notably, aggressive automated HGVs managed to achieve a comparable travel time of about 56.44 seconds but at a higher traffic volume of 1200 vehicles, handling an increase of 200 vehicles with only a minimal rise in travel time. Similarly, normal automated HGVs maintained efficiency by posting a travel time of 53.45 seconds with 1000 vehicles and only slightly increased to 56.28 seconds with 1200 vehicles. Cautious automated HGVs, starting at 58.19 seconds for 1000 vehicles, saw their travel time increase to 70.66 seconds for 1200 vehicles. This pattern across all types of automated HGVs illustrates their capability to manage increased traffic volumes effectively, with aggressive and normal modes particularly demonstrating an ability to maintain travel times close to those of human drivers under less congested conditions.

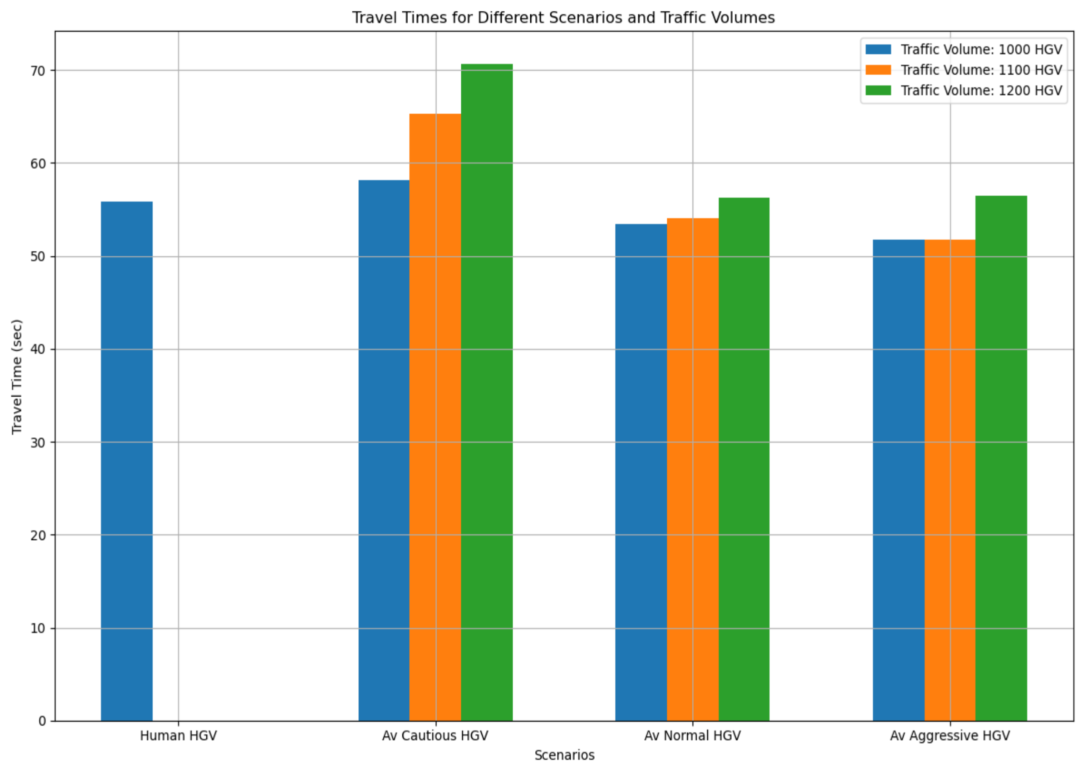

Fig. 9 *Comparative analysis of travel time by driving mode and traffic volume for automated HGVs in intersections*

4.1.3 Average Vehicles Delay Results

At a traffic volume of 1000 vehicles, human-operated HGVs recorded an average vehicle delay of approximately 39.82 seconds as illustrated in Fig. 10. In contrast, aggressive automated HGVs managed to reduce this delay to about 35.76 seconds, and even as traffic volume increased to 1200 vehicles, the delay only slightly rose to 40.44 seconds. Similarly, normal automated HGVs showed an initial delay of 37.43 seconds with 1000 vehicles, which modestly increased to 40.27 seconds with 1200 vehicles. This indicates a minimal rise in delays despite the 200-vehicle increment, highlighting their ability to efficiently manage higher traffic volumes. On the other hand, cautious automated HGVs, while starting at 42.18 seconds for 1000 vehicles, experienced a more substantial increase to 54.66 seconds for 1200 vehicles. This pattern across all types of automated HGVs illustrates their capability to manage increased traffic volumes effectively, with aggressive and normal modes particularly showing an ability to maintain or slightly increase vehicle delays, thereby maintaining operational efficiency even under more demanding traffic conditions.

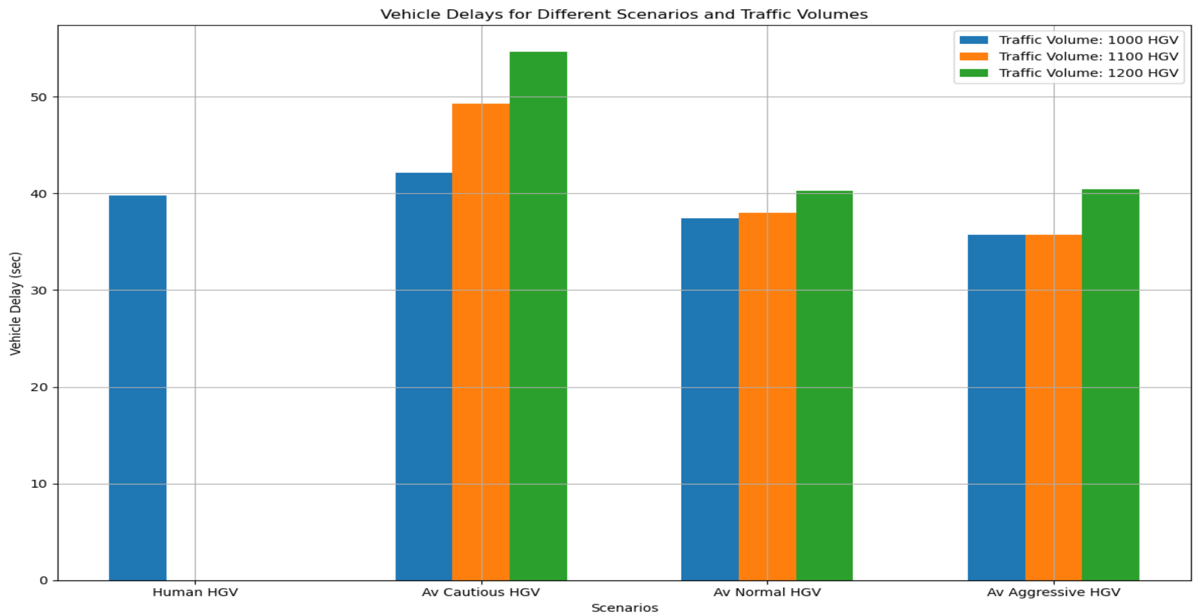

Fig. 10 *Comparative analysis of delay by driving mode and traffic volume for automated HGVs in intersections*

4.1.4 Average Vehicle Gas Emissions and Fuel Consumption Results

The analysis of emissions and fuel consumption data for human and automated HGVs across varying traffic volumes of 1000, 1100, and 1200 vehicles reveals distinct trends in environmental impact and operational efficiency as illustrated in Fig. 11, 12, 13, and 14. At the 1000 vehicle level, human-driven HGVs demonstrated relatively lower emissions of CO, NOX, and VOC, and fuel consumption than their cautious automated counterparts, which recorded the highest figures in all categories. This trend continues as vehicle numbers increase, with cautious automated HGVs consistently showing significantly higher emissions and fuel consumption. On the other hand, aggressive automated HGVs displayed the most efficient operational profile, consistently registering the lowest emissions and fuel usage across all traffic volumes. Normal automated modes also maintained better environmental efficiency than cautious modes but did not achieve the low levels of the aggressive mode. This data underscores a clear efficiency gradient among the driving modes, with aggressive automated HGVs optimizing both emissions and fuel usage, suggesting their superior environmental and operational performance compared to other modes.

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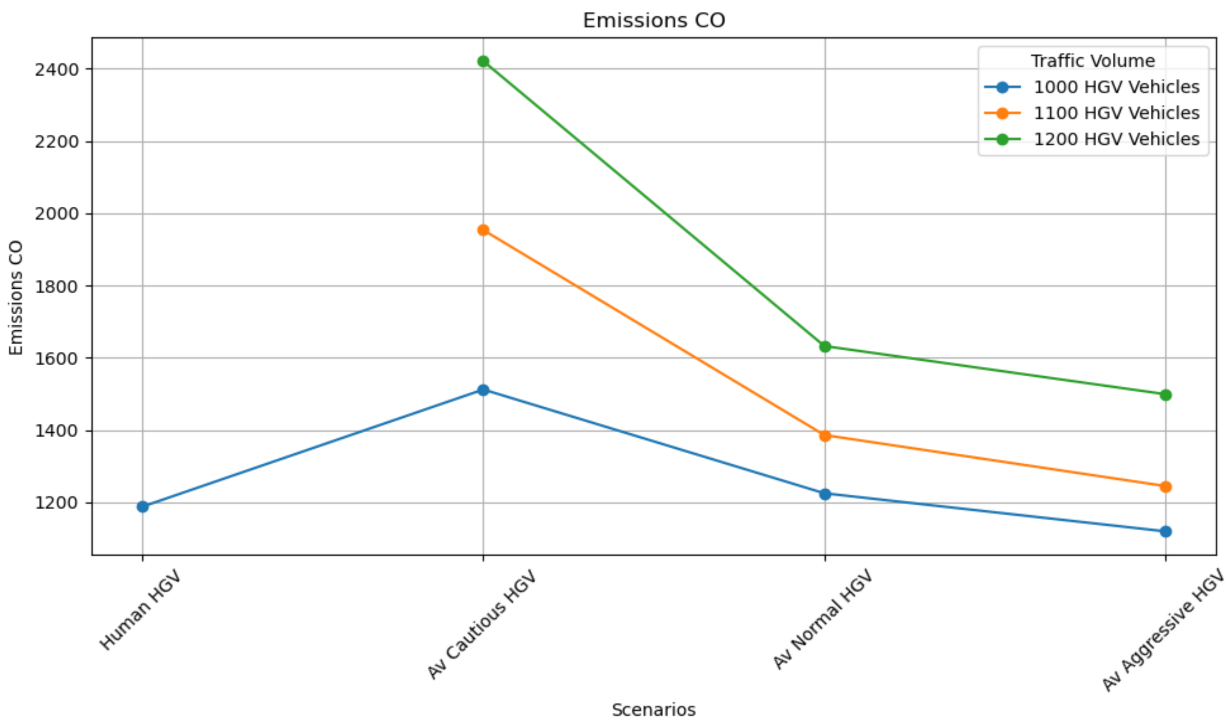

Fig. 11 *Environmental impact of autonomous HGVs driving behaviors on CO emissions in intersections*

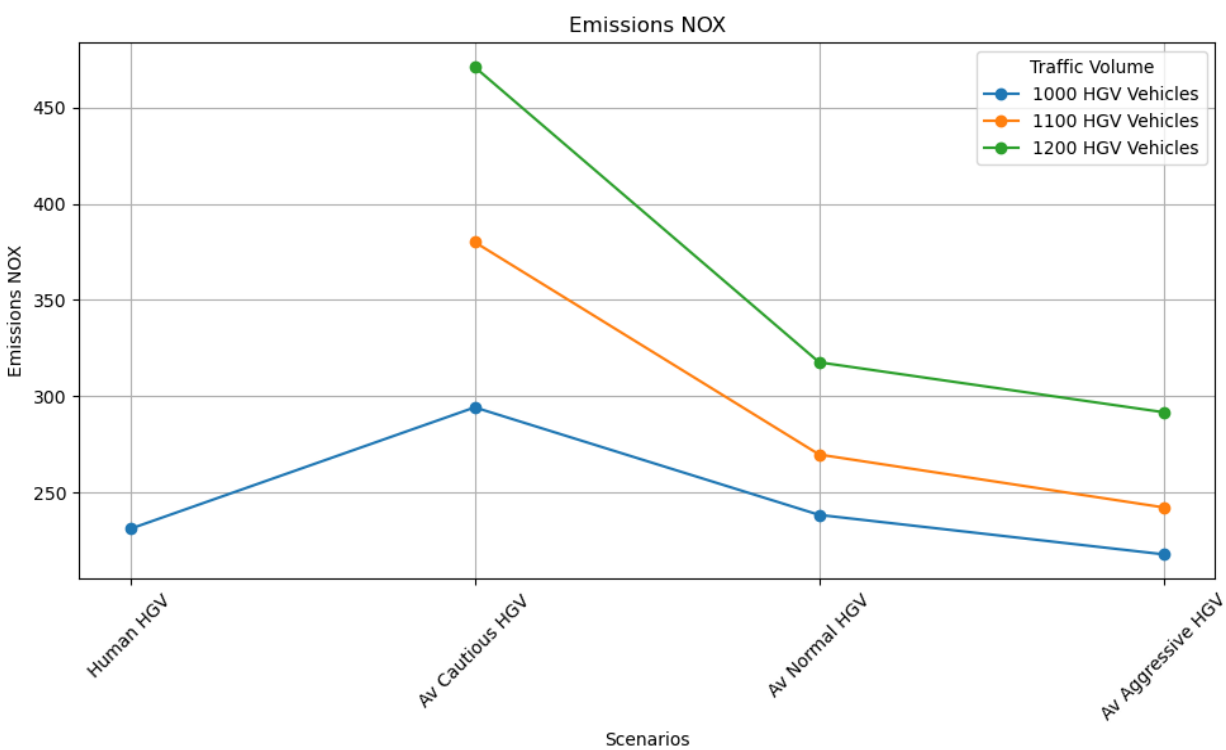

Fig. 12 *Environmental impact of autonomous HGVs driving behaviors on NOX emissions in intersections*

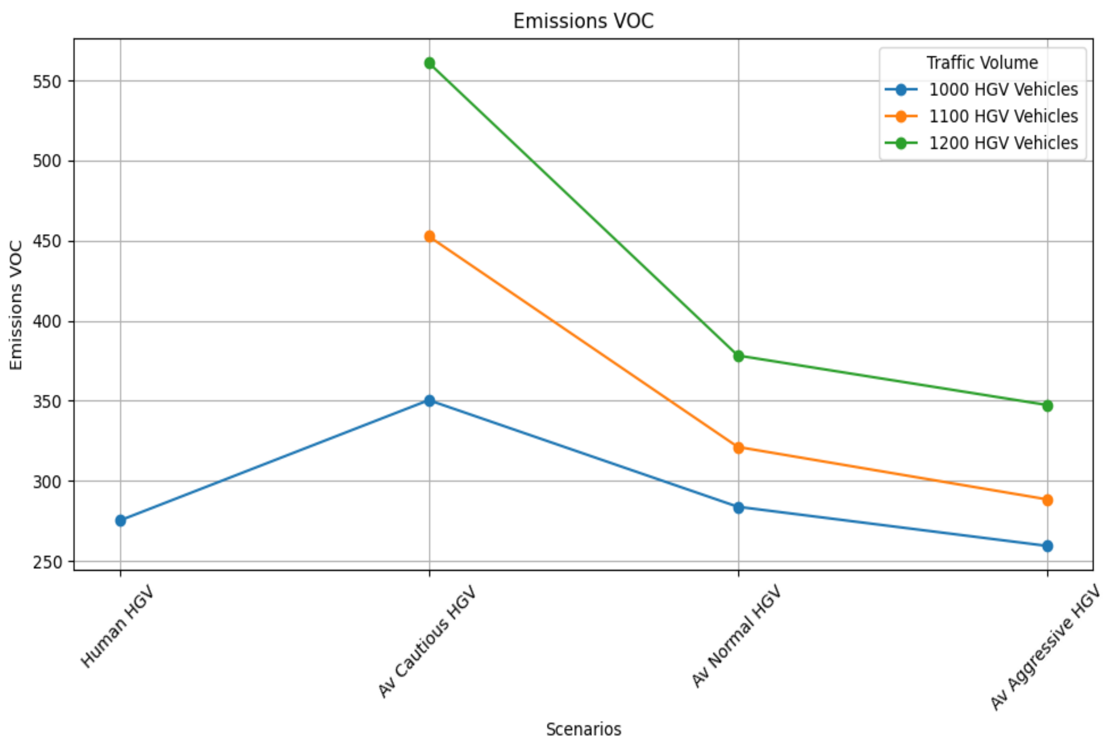

Fig. 13 *Environmental impact of autonomous HGVs driving behaviors on VOC emissions in intersections*

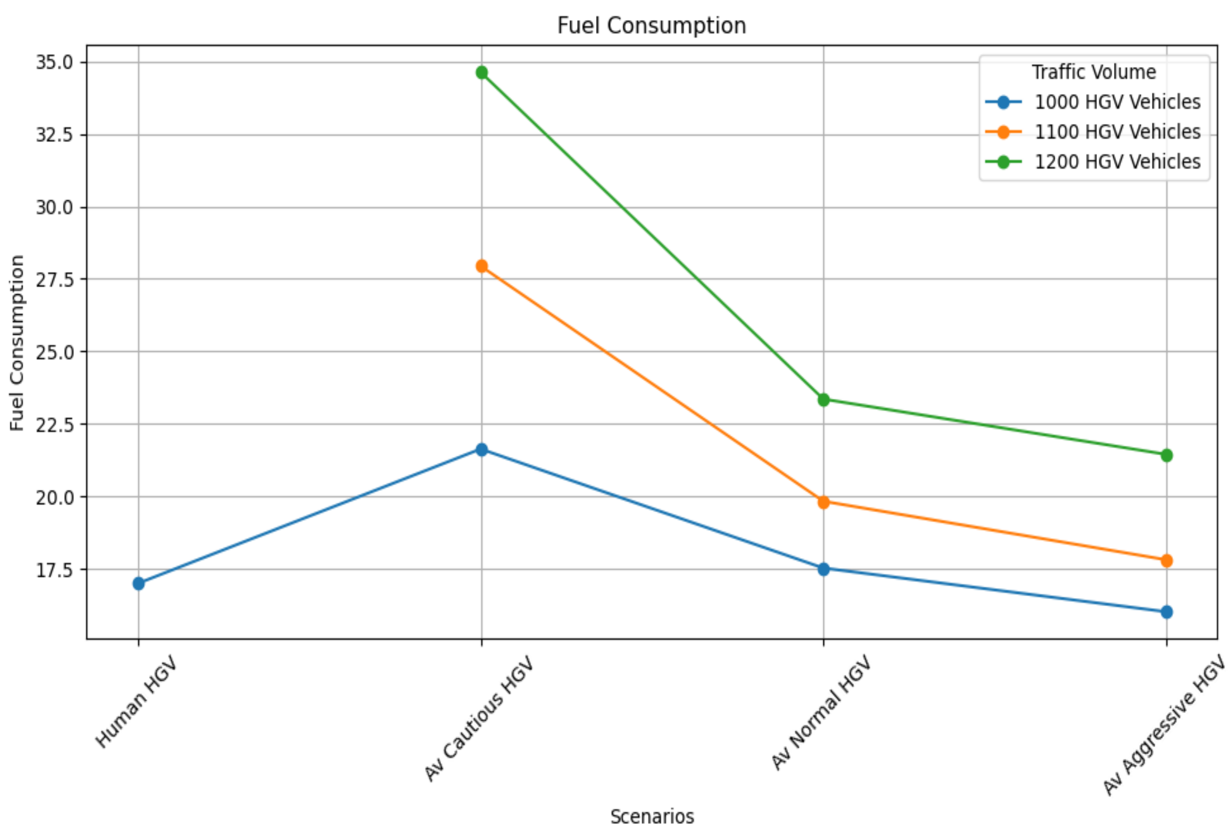

Fig. 14 *Fuel consumption of autonomous HGVs driving behaviors in intersections*

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4.2 Highway Metrics Results Analysis

4.2.1 Average Travel Time Results

The data reveals a clear trend where automated HGVs, particularly in the aggressive mode, consistently outperform human-driven and other automated modes in reducing travel times across increasing vehicle volumes. For instance, with 1000 HGVs, the human-driven vehicles registered the highest travel time at approximately 3646.47 seconds as illustrated in Fig. 15. In contrast, cautious automated HGVs slightly reduced this time to about 3535.86 seconds, and normal automated HGVs further decreased it to 3390.44 seconds. However, aggressive automated HGVs showed the most significant reduction, achieving a travel time of approximately 3159.62 seconds.

The trend of the reduction in travel time by a more aggressive automated mode persisted even as the number of vehicles further increased to 1100 and 1200 HGVs. With 1100 vehicles, aggressive automated HGVs again posted the lowest travel time at about 3165.16 seconds compared to the cautious and normal mode that posted times of 3568.72 and 3400.25 seconds, respectively. With 1200 vehicles, aggressive automated HGVs still had a low travel time of around 3166.57 seconds, indicating that at this particular number, the aggressive mode was still quite efficient even with the high number of vehicles.

This consistent performance of aggressive automated HGVs under different traffic volumes that the potential to improve highway operational efficiency is high, thus insinuating that the adoption of more assertive automated driving settings should yield tremendous improvements, particularly with regard to travel time and general traffic flow under high-density conditions.

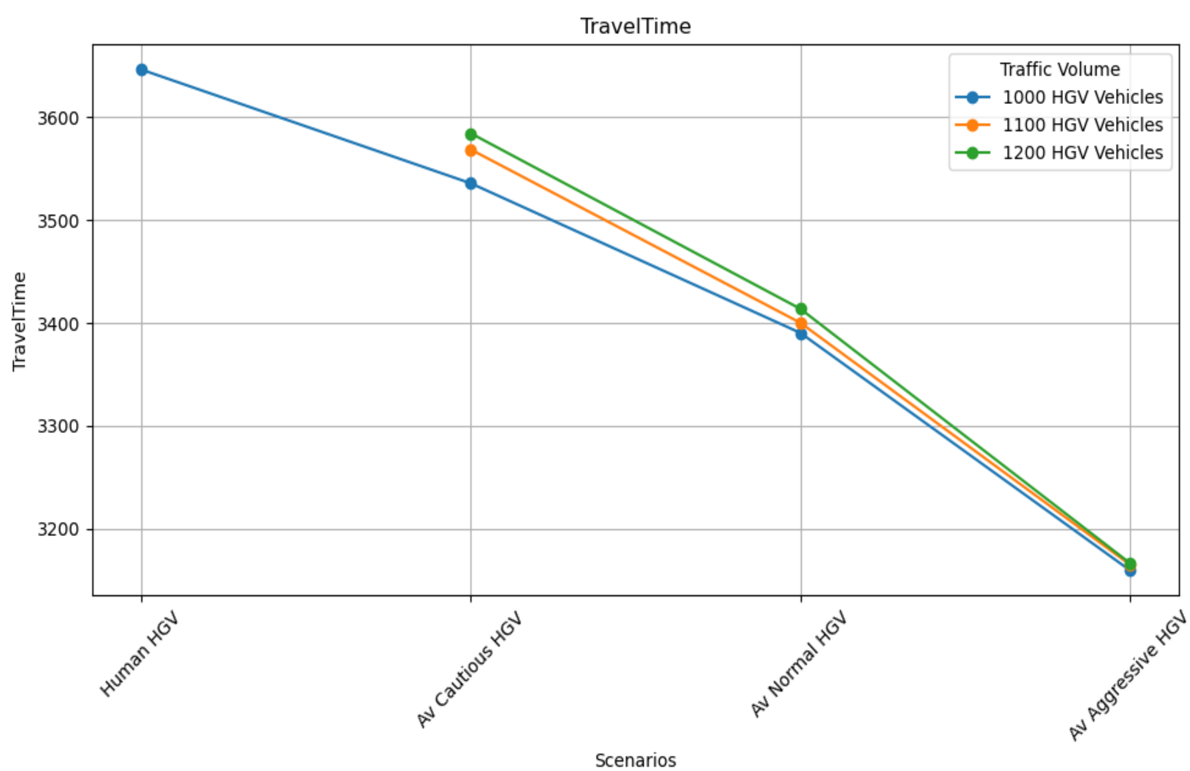

Fig. 15 *Comparative analysis of travel time by driving mode and traffic volume for automated HGVs in highways*

4.2.2 Average Vehicles Delay Results

Analyzing the average vehicle delays across different scenarios for 1000, 1100, and 1200 HGVs highlights the distinct impact of automated versus human driving modes on highway congestion. From Fig. 16, the automated mode has a perceptible effect on congestion, where the vehicle delay for human-operated HGVs was found to be around 89.31 s with 1000 vehicles, as shown in the baseline. The automated HGVs had the following effects, for Cautious automated HGVs the delay was considerably increased to 180.83 s, which conveys that the cautious strategy might lead to increased waiting time for HGVs. For Normal automated HGVs the delay was decreased to 48.61 s, and for Aggressive automated HGVs, the delay was decreased to 34.43 s, conveying that the automated strategy is successful in reducing congestion. This pattern persisted as vehicle volumes increased to 1100 and 1200, with cautious automated HGVs consistently registering the highest delays 216.92 seconds and 217.61 seconds emphasizing their consistent lag in traffic flow. Meanwhile, normal, and aggressive modes maintained comparatively lower delays, particularly aggressive automated HGVs, which effectively kept delays below 50 seconds across all traffic volumes. This analysis underscores the superior performance of aggressive automated HGVs in minimizing vehicle delays and suggests a significant trade-off between the safety-oriented cautious automation and the efficiency-focused aggressive settings in managing high-density traffic on highways.

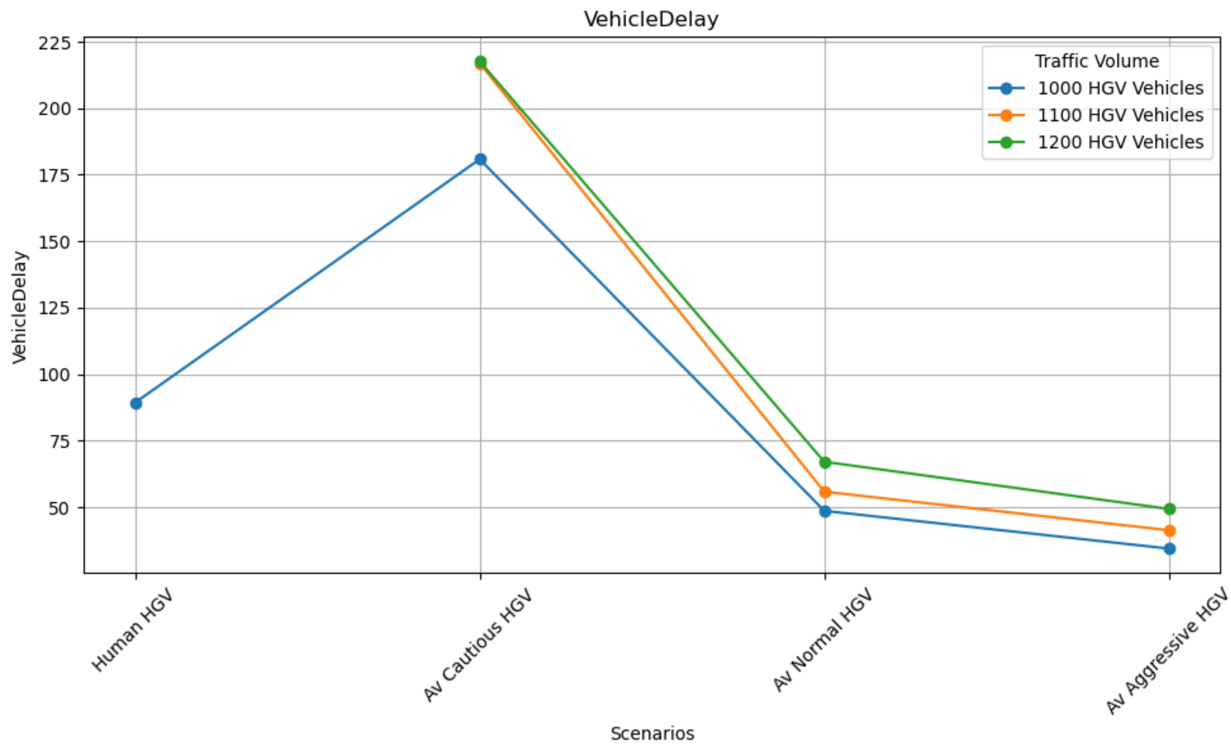

Fig. 16 *Comparative analysis of delay by driving mode and traffic volume for automated HGVs in highways*

4.2.3 AV HGVs Arrival Rates

The analysis of HGV arrival rates for scenarios involving 1000, 1100, and 1200 vehicles provides insights into the efficiency of different driving modes on highway throughput. At the 1000 vehicle level, human-operated HGVs achieved 513 arrivals as illustrated in Fig. 17, setting a baseline for comparison. Automated HGVs, across different modes, improved upon this figure: cautious automated HGVs managed 546 arrivals, while normal automated HGVs increased this to 593 arrivals. Aggressive automated HGVs demonstrated the highest improvement, with 646 arrivals, showcasing their superior capability to handle traffic efficiently. As the vehicle count increased to 1100 and 1200, With 1100 vehicles, aggressive automated HGVs registered 714 as the highest number of arrivals, compared to the 610 arrivals in the cautious automated HGVs setting. The pattern continued with 1200 vehicles, where the aggressive automated HGVs realized a high number of arrivals with 775 compared to 626 and 696 for cautious and normal modes, respectively. The outperformance of aggressive automated HGVs has been quite consistent and can improve operational efficiency, hence exploiting the highway capacity, especially at high vehicle densities, hence it comes as quite promising a way to help in managing the increased traffic flow with more effectiveness.

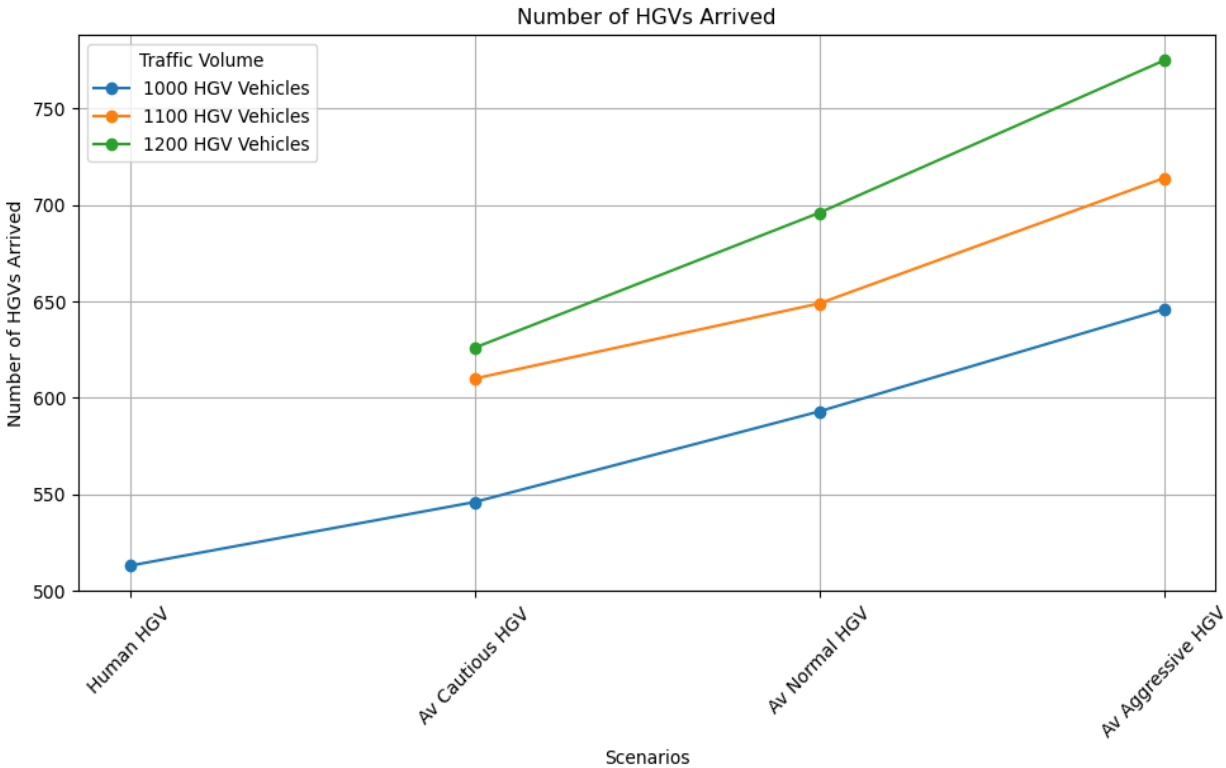

Fig. 17 *Comparison of HGV arrival rates across human and automated driving modes at varying traffic volumes*

5. Conclusion

In conclusion, the extensive analysis of performance metrics for human-operated and automated HGVs both at intersections and on highways provides valuable insights into efficiencies and challenges associated with different driving modes. The data corroborates that automated HGVs, particularly with aggressive configurations of driving, bring up a dramatic gain in operational efficiencies characterized by reduced travel times, diminished vehicle delays, and enhanced arrival rates as the traffic volume increases. Operating aggressively in automated modes on highways proves to be of higher value in managing higher vehicle densities effectively.

Aggressive automated HGVs consistently demonstrate superior performance, show that the aggressive automated HGVs have better performance compared to a variety of scenarios, and hence the technology is one for increasing throughput and decreasing congestion in varied traffic scenarios, whether in highway travel or complex intersection environments. This implies that the cautious automated HGVs, even though they are safer, might lead to relatively higher emissions and fuel consumption, respectively, with longer delays, suggesting a fundamental trade-off between operational efficiency and safety.

Implications of these results are strong for all urban planning, traffic management, and environmental policy. If it can be proven that the most aggressive automatic driving modes reduce delay and increase throughput substantially, a good reason exists for widespread deployment of these modes into mainstream traffic. On the other hand, the trade-offs discovered with the careful driving modes make clear the need for balanced treatment and careful consideration of the effect on safety as well as efficiency.

The automatic driving technology should be further fine-tuned for future adaptability and decision-making abilities under different traffic conditions. Long-term environmental implications, more so on the emission and fuel consumption factors, will be a subject of research with the wide-scale use of automated HGVs. Further refining a hybrid system that can adjust dynamically between aggressive and cautious modes, depending on real-time traffic data.

Policy measures should also allow for the integration of automated vehicles into current infrastructures. It is also important to ensure that the regulatory and guidance systems associated with the safe deployment of automated HGVs leave ample space for encouragement to innovate in this area. Finally, public acceptance and trust in automation need to be built on the principles of transparency, consistent safety records, and clear explanation of the benefits and limitations of the systems.

In sum, introduction of such automated vehicle technologies may be expected to bear much more positive fruit for traffic management and the environment in general, provided concerted efforts are made by researchers, policy makers, and the public. Strategic implementation, with continuous technological advancements and public engagement, would be important to ensure that steps are taken closer to achieving increasingly more efficient and sustainable transportation systems.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The contributions of the authors to the paper are specified as follows: ***Mustafa Albdairi*** *was responsible for data curation, formal analysis, writing the original draft, and validation of the results.* ***Ali Almusawi*** *provided supervision throughout the research process.* ***Syed Shah Sultan Mohiuddin Qadri*** *also contributed to the study's conceptualization and provided supervision. All authors reviewed the results and approved the final version of the manuscript.*

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