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Impact of Aggressive HGV Platoons and Human-Driven Heavy Goods Vehicles on Signalized Intersections Performance

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***Abstract:** This paper presents a study on the performance and environmental impacts of aggressive heavy goods vehicle (HGV) platoons in comparison to human-driven HGVs at a random signalized intersection under varying traffic volumes between 500 and 1500 HGVs. A total of 12 scenarios have been developed, 6 for each of the vehicular behaviors, to quantify the emissions (CO, NOX, VOC) and fuel consumption, travel time, and delays. The analysis is implemented using the PTV VISSIM microscopic traffic flow model. Realization that the majority of the differences in the performance of the two vehicular controls seems to be different as the traffic volume increases was the realization. In most cases, aggressive HGV platoons were found to have lower emissions, in comparison to fuel consumption, while the flow and delay of aggressive HGV platoons were comparatively better against the case with human-driven HGVs. The results have thus provided new avenues for the incorporation of aggressive HGV platoons into urban traffic systems, more so in scenarios that involve a high level of traffic at intersections, as a potentially effective tool for augmenting the efficiency of an intersection and cutting down its environmental impacts. The present study strongly recommends the advancement of traffic management strategies that can capture the dynamics between the two heterogenous traffic flows induced by autonomous and semi-autonomous vehicle technologies.*

***Keywords:** Aggressive HGV Platoons, Human-Driven Heavy Goods Vehicles, Signalized Intersection Efficiency, Ptv Vissim, Emissions and Fuel Consumption in Traffic, Queue Metrics.*

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1. INTRODUCTION

Heavy goods vehicles are vital modes of transporting goods and sustaining the movement of economic activities in modern urban centres [1-3]. Nevertheless, they are the major sources of traffic congestion and environmental pollution at signalized intersections where the traffic volumes meet in developing countries [4, 5]. With advancements in autonomous vehicle technology, the potential to mitigate these challenges has garnered considerable attention [6-9]. Therefore, putting into consideration the possibility of reducing these adverse effects with the evolution of autonomous vehicle technology, this study aims to analyze the operational and environmental impacts of aggressive HGV platoons compared to human-driven HGVs at signalized intersections, considering the range of traffic volumes between 500 and 1500 HGVs.
Aggressive HGV platooning, the phenomenon of having vehicles closely spaced with coordinated maneuvers, may offer an opportunity to enhance intersection efficiency and reduce emissions. This paper aims to make an analysis of the relative performances between these two vehicle behaviors under a range of traffic conditions using advanced traffic simulation tools such as PTV VISSIM. The performance evaluations on the emitted gases (CO, NOX, VOC), fuel consumption, travel time, and delay measures will be conducted to understand the subtle impacts of each vehicular control strategy.
Understanding how the diverse behaviors of various vehicles interact with different volumes of traffic at a signalized intersection gives an idea of possible measures for effective traffic management and strategies that encourage transportation systems. Elaboration of potential benefits of the aggressive HGV platoons will contribute to the growing scope of studies targeted at the optimal urban mobility dimension that possesses an environmentally conscious aspect. It further specifies that emerging technologies need to be integrated within the existing infrastructures to address the complex challenges emerging in urban freight transportation.
This paper thus aimed to inform policymakers, transportation planners, and industry stakeholders about the implications involved in the adoption of aggressive HGV platoons in the urban traffic systems. Ultimately, the findings from this research support evidence-based decisions or, at least, give reasonable insight into the implications following aggressive HGV platoons in the context of freight transportation networks.

2. LITERATURE REVIEW

The area of focus on HGV platooning allows studying this in the general framework for efficiency and sustainability improvements in freight transportation. The impacts that platooning brings to fuel consumption, traffic flow, and infrastructure use have been studied in many simulation models and real testing in so many ways. However, there is still a big gap in the study regarding the behavior of platoons under aggressive conditions of autonomous HGV platoons. While the study touched on some merits of the cooperative and adaptive platooning systems, the analysis of performance of aggressive platoons, especially in mixed traffic environments, still needs to be well study-analyzed. This study aims to address this gap by evaluating the operational and environmental implications of aggressive autonomous

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HGV platoons compared to human-driven counterparts, focusing on their behavior at signalized intersections across varying traffic volumes. Through detailed simulation and analysis, this research endeavors to provide valuable insights into the effectiveness and feasibility of aggressive platooning strategies in improving intersection efficiency and reducing environmental impacts in urban freight transportation.

Table 1. Summary of Studies Investigating the Impact of HGVs on Transportation Systems.

Reference	Year	Objective	Methodology/Tools Used	Key Findings
[10]	2015	Develop a simulation platform for HDV platooning in mixed traffic and assess its impacts.	Microscopic simulation with detailed HDV platoon modeling; Analytical fuel consumption model.	HDV platooning with Cooperative Adaptive Cruise Control (CACC) improves transport efficiency, fuel savings, and safety. It can save fuel with over 40% penetration rate. Positive impacts on traffic flow, capacity, and fuel efficiency.
[11]	2016	Model and analyze heavy-duty vehicle platooning to address infrastructure challenges, energy consumption, and environmental impacts associated with freight transport.	Modeling and analysis	Study highlights freight transport demand growth, increasing traffic intensity, and the need to address infrastructure pressure and energy usage through heavy-duty vehicle platooning.
[12]	2018	Develop a network-wide coordination system for heavy-duty vehicle platooning to reduce fuel consumption in road freight transport.	Network-wide coordination system	Reduced fuel consumption in heavy-duty vehicle platooning. Study emphasizes the dominance of road freight in overland transport and the need to address it through platooning.
[13]	2021	Assess the impact of multi-class heavy-duty	Infra-Red sensor-based device; Simultaneous	Speed and flow rates decrease significantly due to heavy-duty vehicles' influence, with

		vehicles on traffic stream characteristics of highway lanes under mixed traffic environments.	equations approach	the most significant impact observed in Median Lanes. The study underscores the importance of understanding how platooning affects traffic flow mix on highways.
[14]	2021	Investigate the impact of heavy vehicle platoons on bridge traffic loads, aiming to inform policymakers and bridge authorities during the transportation revolution.	Simulations; Weigh-in-motion technology	Study highlights the potential impact of platoons on bridge traffic loads and emphasizes the importance of considering these effects in future transportation planning and policymaking.
[15]	2022	Investigate the operational impact of heavy commercial vehicle platooning on urban arterials with signal prioritization.	Micro-simulation models (PTV VISSIM)	Traffic signal prioritization (TSP) can mitigate the impact of heavy commercial vehicle (HCV) platooning on traffic congestion. However, higher HCV platooning rates may lead to significant traffic delays, posing challenges for traffic management on urban arterials.
[16]	2022	Analyze the influence of heavy transport vehicle (HTV) platooning on the traffic flow mix of intercity highways.	Infra-Red sensor device	HTVs operating at low speeds reduce speed-flow characteristics significantly, impacting traffic flow mix on highways. Platooning of HTVs obstructs traffic flow, especially in high-speed lanes. The study emphasizes the need to manage HTV platooning for optimal traffic flow.
[17]	2022	Develop a robust platoon control system for heavy-load autonomous industrial	Distributed control law; Feedback linearization control	Study emphasizes the need for robust platoon control systems for heavy-load autonomous industrial vehicles operating in

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		vehicles, focusing on practical applications and addressing challenges in dynamic environments.		complex, unstructured environments to ensure safety and efficiency.
[18]	2023	Develop a truck platooning system with an emergency braking function and validate its effectiveness through real vehicle-in-the-loop testing.	Vehicle-to-vehicle (V2V) communication technology; Real vehicle-in-the-loop (VIL) testing	Difficulty in maintaining targeted intervehicle distance for fuel efficiency and safety observed. Critical safety issues in emergency braking for heavy-duty trucks are highlighted.

3. METHODOLOGY

3.1 Signalized Intersection

The signalized intersection selected for this study was modeled after a randomly chosen intersection located in Kirkuk, Iraq. This intersection, depicted in Figure 1 and 2, is a standard four-legged configuration commonly found in urban areas. The signal control at this intersection follows a predetermined cycle time of 96 seconds, as illustrated in Figure 2.

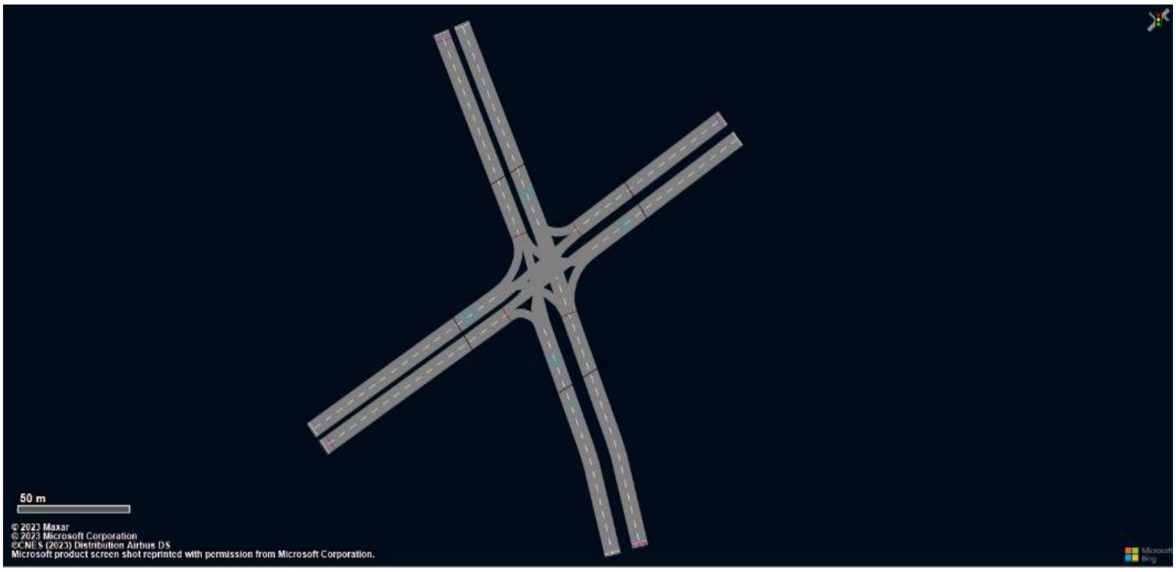

Fig.1 The Examined Signalized Traffic Intersection.

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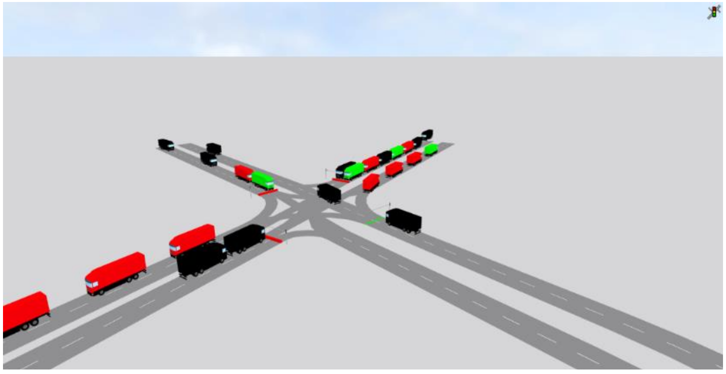

Fig.2 3D Visualization of the Examined Signalized Traffic Intersection.

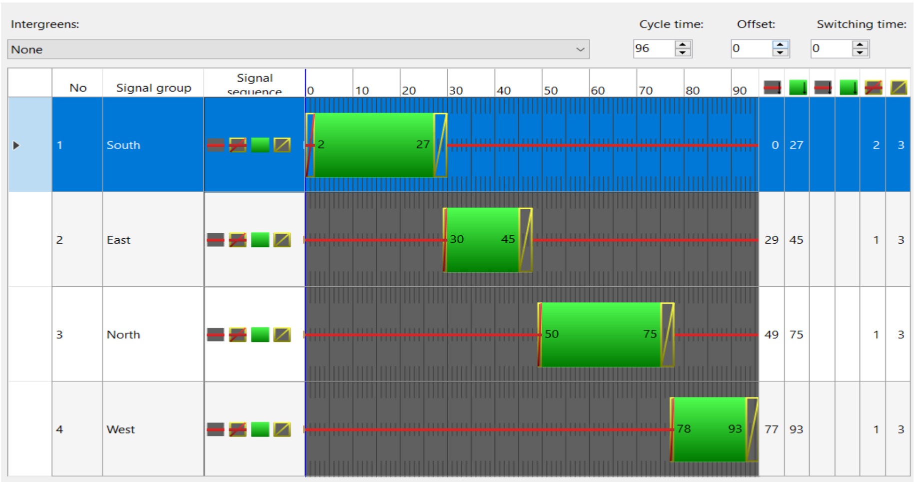

Fig.3 The Configuration of Traffic Signals of the Examined Signalized Traffic Intersection.

The examined traffic volume ranges were randomly selected, spanning from 500 heavy goods vehicles (HGVs) to 1500 HGVs. This broad spectrum of traffic volumes encompasses varying degrees of vehicular density, reflecting real-world scenarios encountered in urban freight transportation.

Table 2. Summary of the traffic volumes examined at the intersection.

Total Traffic Volume	**Bound**	**HGVs Count**	**Movement Ratio**		
			Right	**Straight**	**Left**
500 HGV	North	150	.333	.333	.333
	East	100	.333	.333	.333
	South	150	.333	.333	.333
	West	100	.333	.333	.333
700 HGV	North	200	.333	.333	.333
	East	150	.333	.333	.333
	South	200	.333	.333	.333
	West	150	.333	.333	.333
900 HGV	North	250	.333	.333	.333

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	East	200	.333	.333	.333
	South	250	.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
1300 HGV	North	350	.333	.333	.333
	East	300	.333	.333	.333
	South	350	.333	.333	.333
	West	300	.333	.333	.333
1500 HGV	North	400	.333	.333	.333
	East	350	.333	.333	.333
	South	400	.333	.333	.333
	West	350	.333	.333	.333

3.2 Experimental Design

3.2.1 Car Following Model Parameters

Human drivers commonly follow conventional car-following models, which are influenced by the current traffic conditions and can lead to different reaction times. On the other hand, autonomous vehicles (AVs) with aggressive platoons, affecting their ability to maintain suitable following distances and react to changing traffic situations. The precise parameters governing these behaviors are outlined in Table 3.

Table 3. Parameters of Car Following Model for Different HGVs Behavior.

Wiedemann 99 following model parameters	**AV HGV Aggressive Platoons**	**Human HGV**
CC0 Standstill distance	1.00 m	1.50 m
CC1 Gap time distribution	0.6 s	0.9 s
CC2 ‘Following’ distance oscillation	0.00 m	4.00 m
CC3 Threshold for entering ‘Following’	-6.00	-8.00
CC4 Negative speed difference	-0.10	-0.35
CC5 Positive speed difference	0.10	0.35
CC6 Distance dependency of oscillation	0.00	11.44
CC7 Oscillation acceleration	0.10 m/s^2	0.25 m/s^2
CC8 Acceleration from standstill	4.00 m/s^2	3.50 m/s^2
CC9 Acceleration at 80 km/h	2.00 m/s^2	1.50 m/s^2
Max No. of HGVs in Platoon	7	-
Gap Time	0.6 s	-
Minimum Clearnce	2.00 m	-

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3.2.2 Lane Change Model Parameters

In the study, lane change model parameters are meticulously adjusted to mirror the diverse driving behaviors observed in autonomous heavy goods vehicles (AV HGVs) and human drivers, with the aim of accurately replicating real-world driving scenarios. While advanced merging capabilities are universally enabled, cooperative lane change functionality is exclusively activated for AV HGVs, underscoring a significant technological gap between AVs and human-operated vehicles. However, the reduction factor of the safety distance has been varied across groups and observed as 0.75 meters for the AV aggressive platoon mode and 0.60 meters for human drivers. The minimal clearance (front/rear) also carries different values and has been considered as 0.50 meters for the AV aggressive platoon mode, according to the safety requirements. The cooperative braking maximum deceleration also carries different values for these investigations, such as −6.00 m/s² for the AV aggressive platoon and −3.00 m/s² for human drivers. In this way, differences in handling large decelerations/dramatic braking are represented within the traffic flow. The mean input parameters, described above and shown in Table 4, are important for this simulation to observe the response of different driving modes under different traffic conditions, which would ensure a better understanding of AV HGV dynamics within a mixed-traffic environment.

Table 4. Parameters of Lane change Model for Different HGVs Behavior.

Parameter's	**AV HGV Aggressive Platoons**	**Human HGV**
Advanced merging	on	on
Cooperative Lane change	on	off
Safety distance reduction Factor	0.75	0.60 m
Min clearance (front/rear)	0.50 m	0.50 m
Maximum deceleration for Cooperative braking	-6.00 m/s2	-3.00 m/s2

3.2.3 Speed Distribution

Speed distributions for both conventional and AV HGV aggressive platoons were determined to project real-world conditions convincingly in the simulation. Speeds in the intersection were selected in such a way that they lie in the range of 40 km/h to 45 km/h, as can be seen in Figure 4, which is quite realistic regarding urban traffic. In this manner, it is guaranteed that the vehicle will behave in the simulation environment as it would. In the case of the simulation, realistic speed distributions lead to realistic speed values, which become very important in understanding variance in vehicle speeds and how such variance affects the dynamics of traffic flow. Therefore, the performance analysis of the intersection is more credible, and genuine insights may be drawn on the influence of AV technology on HGV operation.

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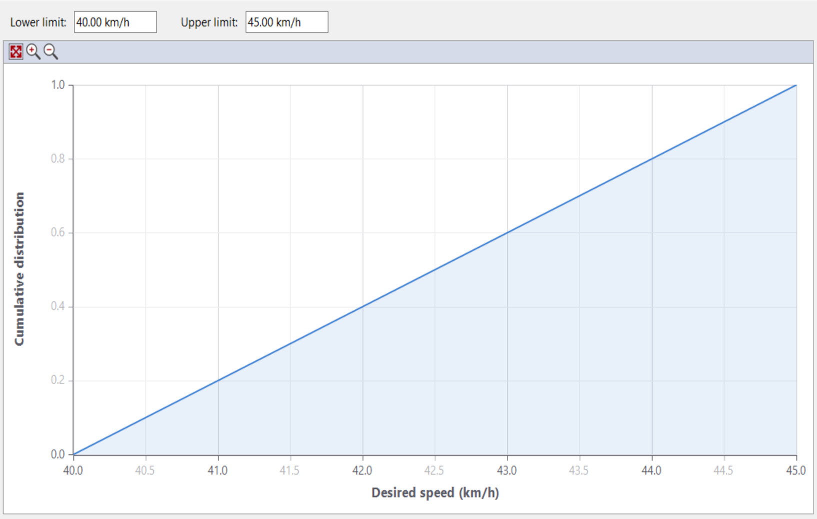

Fig.4 Speed Distribution of both Conventional HGVs and AV HGV Aggressive Platoons in the Intersection.

3.2.4 Experimental Scenarios

This current study has conducted experimental scenarios, and hence the critical analysis of the traffic dynamics and performance evaluation through the Intersection under varying settings has been carried out. Different scenarios have been designed by properly simulating modeling from the behavioral dynamics of the automated Heavy Goods Vehicles under different volumes of traffic. The base volume of HGVs that are set at 500, ranging from the increase of 700, 900, 1100, 1300, and 1500 HGVs as shown in Table 5. This methodology provides a proper analysis of the dynamics of traffic flow under different densities of vehicles and an offer of deep understanding of the operations of the HGV across different traffic scenarios.

Table 5. Summary of Experimental Scenarios.

Traffic Volume	Scenario
500 HGV	Scenario 1 (100% Human HGV)
	Scenario 2 (100% AV Aggressive HGV Platoons)
700 HGV	Scenario 3 (100% Human HGV)
	Scenario 4 (100% AV Aggressive HGV Platoons)
900 HGV	Scenario 5 (100% Human HGV)
	Scenario 6 (100% AV Aggressive HGV Platoons)
1100 HGV	Scenario 7 (100% Human HGV)
	Scenario 8 (100% AV Aggressive HGV Platoons)
1300 HGV	Scenario 9 (100% Human HGV)
	Scenario 10 (100% AV Aggressive HGV Platoons)

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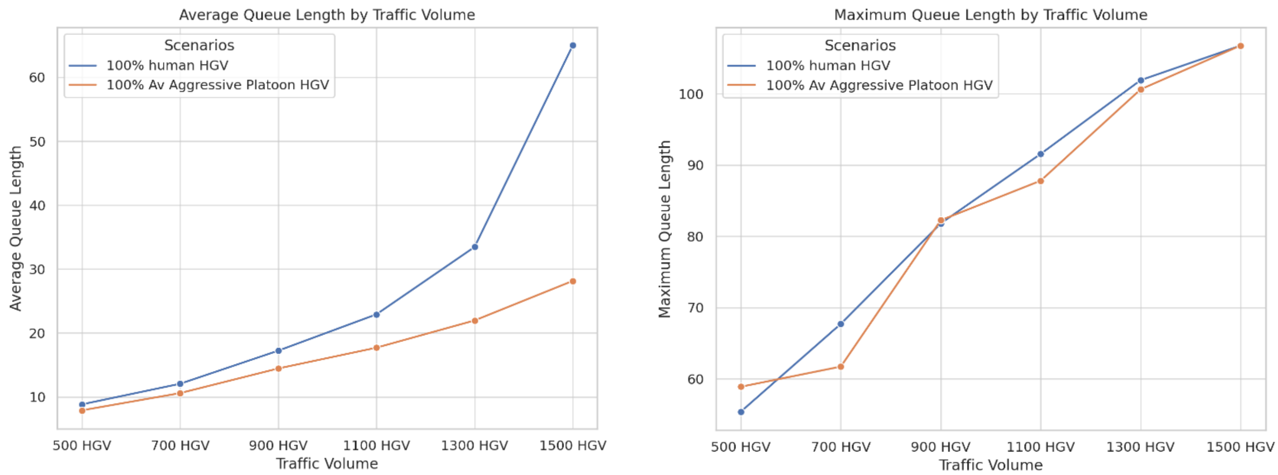
1500 HGV	Scenario 11 (100% Human HGV)
	Scenario 12 (100% AV Aggressive HGV Platoons)

4. RESULTS AND DISCUSSION

The experimental scenarios were designed in such a way to compare human-driven heavy goods vehicles (HGVs) with fully automated aggressive platoon HGVs for various traffic volumes. In this light, among major metrics that define the queue, there is a noticeable gap between Qlen, QlenMax, Qstops, and queue delay.

However, the queue length decreased to 7.90 units for the aggressive platoon HGVs with autonomy. Likewise, the maximum queue length decreases with respect to the human-driven HGVs to 58.87 units for the case of autonomous aggressive platoon HGVs. The number of stops is also reduced from 91.25 stops of human-driven HGVs to 88.25 stops in the case of autonomous aggressive platoon HGVs. Likewise, the queue delay is also reduced to 25.30 units for autonomous aggressive platoon HGVs from 27.41 in the case of human-driven HGVs.
As the traffic volume increased to 1500 HGVs, significant disparities emerged between the two scenarios. Human-driven HGVs exhibited a substantially higher queue length of 64.98 units, whereas autonomous aggressive platoon HGVs maintained a much lower queue length of 28.15 units. Similarly, the maximum queue length for human-driven HGVs soared to 106.77 units, while for autonomous aggressive platoon HGVs, it remained consistent at 106.77 units. The number of stops for human-driven HGVs skyrocketed to 545.75 stops, whereas for autonomous aggressive platoon HGVs, it was significantly lower at 337 stops. Additionally, the queue delay for human-driven HGVs surged to 94.91 units, while for autonomous aggressive platoon HGVs, it was substantially lower at 34.17 units.
These results, illustrated in Figures 4(a)-(d), underscore the significant impact of autonomous aggressive platoon HGVs on traffic performance metrics, particularly in reducing queue length, number of stops, and queue delay, even as traffic volumes escalate.



(a) (b)

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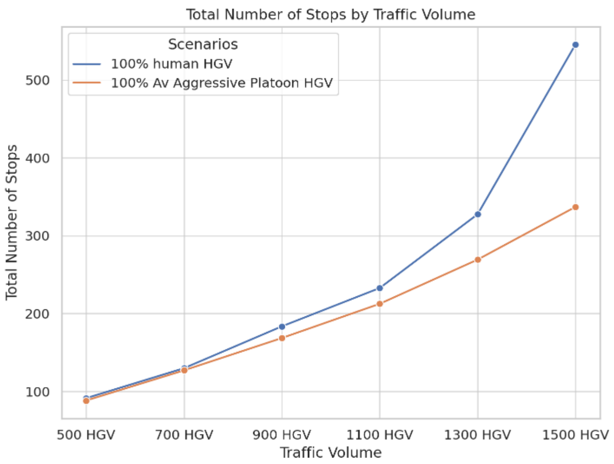
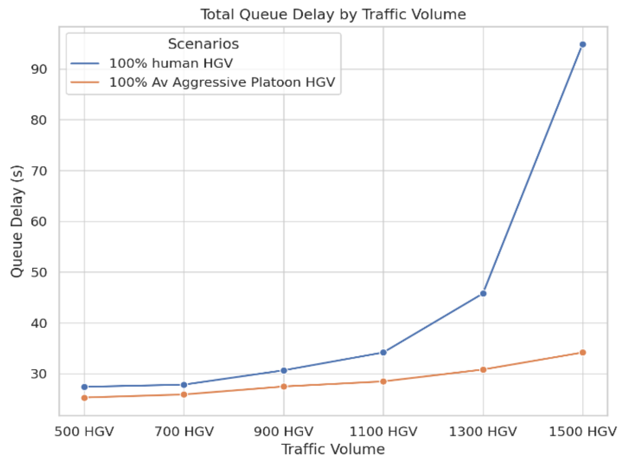


(c)



(d)

Fig.5 Traffic Performance Metrics Comparison (a) Queue Length (Qlen) (b) Maximum Queue Length (QlenMax) (c) Number of Stops (Qstops) (d) Queue Delay

The outcomes of the experimental scenarios conducted to assess travel time, stopped delay, and vehicle delay for human-driven heavy goods vehicles (HGVs) versus autonomous aggressive platoon HGVs across varying traffic volumes.

At a traffic volume of 500 HGVs, both scenarios exhibited similar travel times, with human-driven HGVs recording 54.43 units and autonomous aggressive platoon HGVs registering 53.50 units. Stopped delay and vehicle delay were also comparable between the two scenarios, with human-driven HGVs experiencing 24.63 units and 33.20 units, respectively, and autonomous aggressive platoon HGVs encountering 24.19 units and 32.35 units, respectively.

As the traffic volume increased to 1500 HGVs, significant disparities emerged between the two scenarios. Human-driven HGVs exhibited substantially higher travel times, stopped delays, and vehicle delays compared to autonomous aggressive platoon HGVs. Specifically, travel time for human-driven HGVs surged to 113.84 units, while for autonomous aggressive platoon HGVs, it remained much lower at 62.11 units. Similarly, stopped delay and vehicle delay for human-driven HGVs soared to 71.91 units and 92.59 units, respectively, whereas for autonomous aggressive platoon HGVs, they were significantly lower at 30.41 units and 41.02 units, respectively.

These results, depicted in Figures 6(a)-(c), highlight the substantial benefits of employing autonomous aggressive platoon HGVs in terms of reduced travel times and delays, particularly as traffic volumes escalate.

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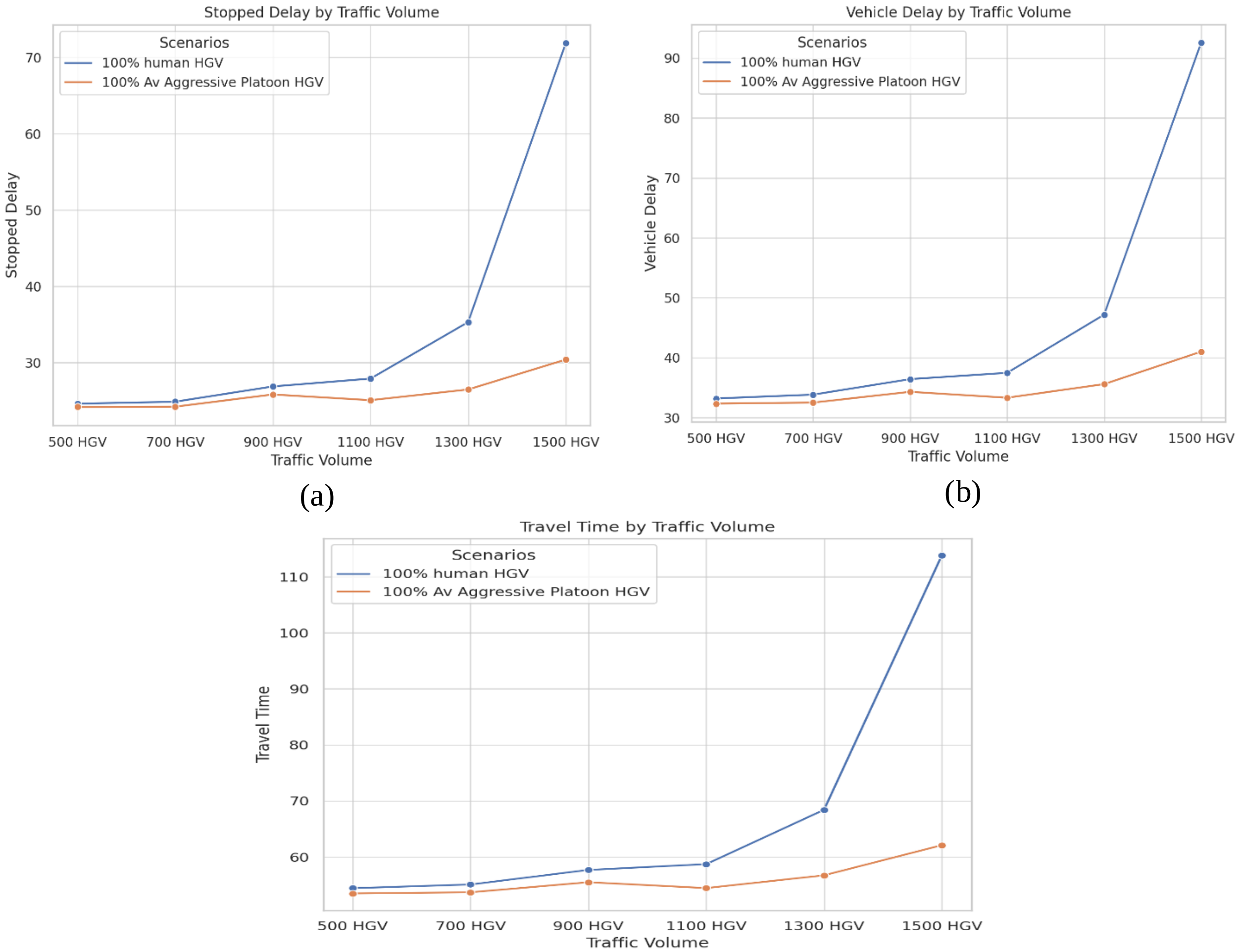

(a) (b) (c)

Fig.6 Comparison of Travel Time and Delay Metrics (a) Stopped Delay (b) Vehicle Delay (c) Travel Time

The emissions of carbon monoxide (CO), nitrogen oxides (NOX), volatile organic compounds (VOC), and fuel consumption for human-driven heavy goods vehicles (HGVs) compared to autonomous aggressive platoon HGVs across varying traffic volumes.

At a traffic volume of 500 HGVs, both scenarios exhibited similar emissions and fuel consumption patterns. For human-driven HGVs, the emissions of CO, NOX, and VOC were 466.44, 90.75, and 108.10 units, respectively, with a fuel consumption of 6.67 units. Autonomous aggressive platoon HGVs showed slightly lower emissions and fuel consumption, with CO emissions at 458.29 units, NOX emissions at 89.17 units, VOC emissions at 106.21 units, and fuel consumption at 6.56 units.

As the traffic volume increased, emissions and fuel consumption also rose for both scenarios. However, notable differences were observed between human-driven HGVs and autonomous aggressive platoon HGVs. For instance, at a traffic volume of 1500 HGVs, human-driven HGVs exhibited substantially higher emissions and fuel consumption compared to

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autonomous aggressive platoon HGVs. Specifically, CO emissions for human-driven HGVs reached 2790.41 units, while for autonomous aggressive platoon HGVs, they were significantly lower at 1705.43 units. Similarly, in the autonomous aggressive platoon HGV scenario, the NOX emissions, VOC emissions, and fuel consumption were significantly lower compared to those of the human-driven HGV scenario.
These results, depicted in Figures 7(a)-(d) below, imply there is a distinct benefit of deploying aggressive platoon HGVs autonomously in terms of emissions and fuel consumption, particularly at higher traffic intensities.

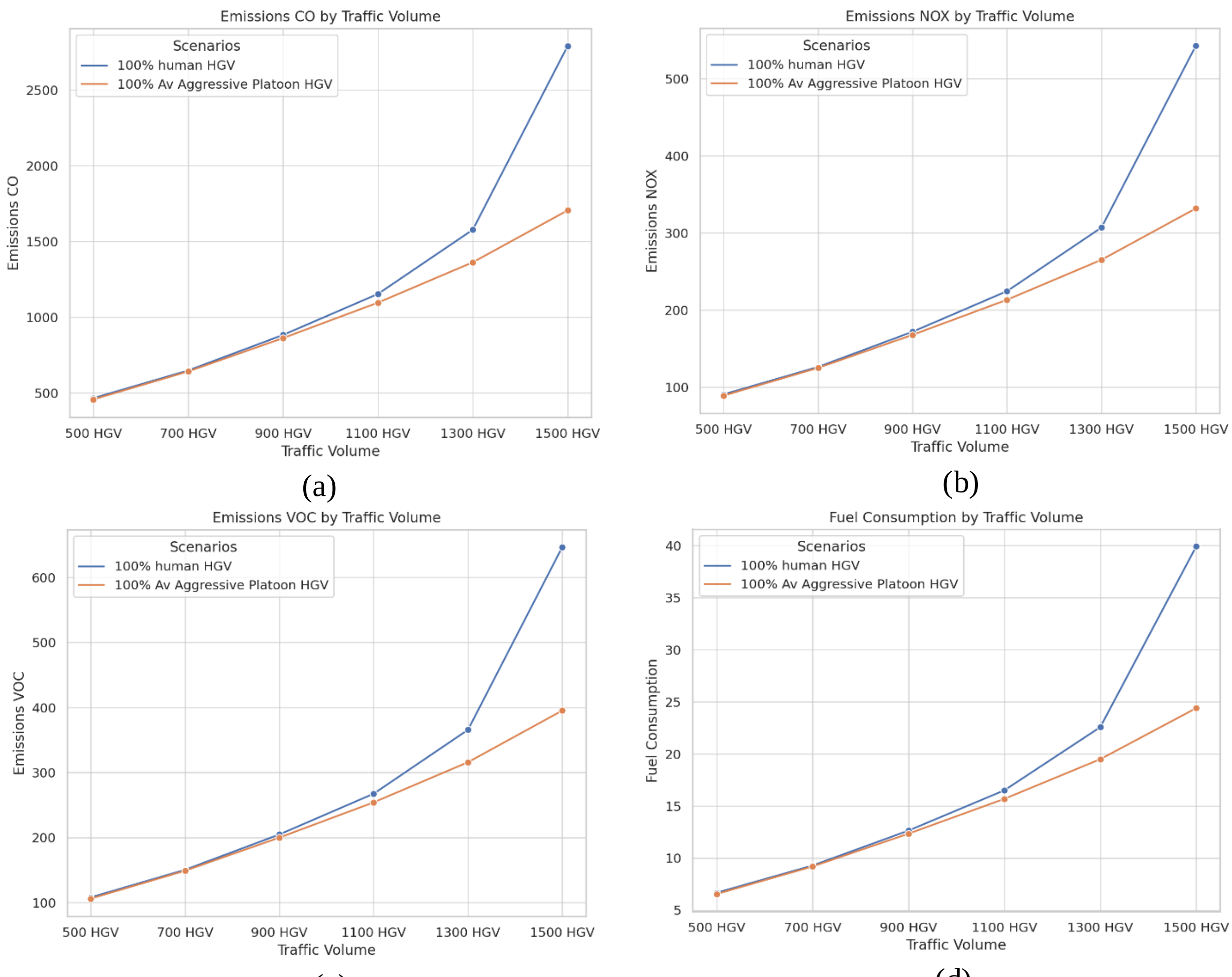

Fig.7 Comparison of Emissions and Fuel Consumption (a) Emissions CO (b) Emissions NOX (c) Emissions VOC (d) Fuel Consumption

5. CONCLUSIONS

The obtained results show that aggressive platooning of HGVs with autonomous control is very promising in realizing the vision of a freight and urban traffic revolution. The results imply massive benefits from the autonomous platooning technology for travel time and fuel

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consumption efficiency, as well as huge environmental considerations. With the aggressive platooning of autonomous HGVs characterized by an increase in the throughput at a higher reduction in the queue length, emissions, and fuel consumption, the problem of congestion and pollution would be a thing of the past as far as efficiency in the urban transport network is concerned. The real concerns taken seriously issues of safety and policy implications that hinge on the mass acceptance of autonomous platooning technologies in the future. Greater merit in research should be given to the further investigation of matters such as the safety assessment, the regulatory framework, and the infrastructural requirements needed for the smooth and effective integration of autonomous HGVs in real-world transport systems. Cooperation among different stakeholders and further innovation will be required to fully harness the potential of autonomous platooning for a more sustainable and efficient transport ecosystem.

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