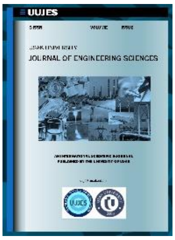

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Review article

IMPACT OF AUTONOMOUS VEHICLE DRIVING BEHAVIORS ON SIGNALIZED INTERSECTION PERFORMANCE: A REVIEW

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Abstract

The use of autonomous vehicles (AVs) in transportation at signalized intersections is proposed to improve safety, efficiency, and sustainability. The discussion shall thus focus more on the impacts of different AV driving behaviors to some key transportation metrics solely at signalized intersections. Among the parameters considered are travel time, queue length, delay, and speed.
This is clear from one such holistic study that Cautious AV behavior would reduce accidents, but on the other way around, it might increase traffic delays and lead to congestion at signalized junctions. Aggressive AVs will improve the flow of traffic but face problems in safety in this kind of set-up. Normal AV operation A balanced approach that offers intermediary levels of travel time and safety.
The review further investigates the environmental effects of various driving patterns within signalized intersections, where it notes that there are noticeable differences in emissions and fuel consumed if the driving behavior is taken into consideration. It goes further into the implications for traffic management and control systems, noting challenges and opportunities while integrating AVs into existing infrastructure and spotlighting at signalized intersections.
Paramount to the review are the considerations of safety, regulatory frameworks, and mitigating strategies relevant to AV behavior at signalized intersections. In so doing, this review seeks to inform future research and policy decisions with a nuanced understanding of how various AV driving behaviors affect signalized intersection performance, seeking to optimize AV benefits while mitigating possible risks at critical traffic junctures.

Keywords: *Autonomous vehicles; driving behaviors; cautious mode; normal mode; aggressive mode; transportation systems; highway performance; intersection efficiency.*

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1. Introduction
1.1 Background

The emergence of autonomous vehicles (AVs) marks a pivotal moment in the evolution of transportation systems worldwide. AVs can travel roadways using algorithms and sensor arrays, implemented with absolute sophistication, that promise to deliver transportation solutions much safer, more efficient, and environmentally sustainable than those produced by human drivers [1, 2].
The potential benefits of AVs are multiple and wide-ranging. Improvement in road safety lights out as one of the leading benefits, whereby AVs would have the potential to cut, at the greatest level, significantly the level of accidents caused by human error such errors remain one of the main causes of fatal traffic crashes worldwide [3]. Improve road safety with the capability to sense potential hazards, predict dangerous situations more quickly and accurately than the reflexes of human beings. such as those by [22], which investigate the factors leading to traffic accidents in specific regions, underscore the critical need for technologies that can enhance predictive capabilities and situational awareness to prevent such accidents. Improve road safety with the capability to sense potential hazards, predict dangerous situations more quickly and accurately than the reflexes of human beings.
Some of those possibilities are that AVs will increase safety on roads and could help reduce cases of traffic congestion, a problem more appropriately termed as an affliction of urban development. Through optimum routing algorithms and dynamic traffic management systems, AVs could effectively work in complex traffic situations, hence reducing bottlenecks and easing congestion on heavily congested roads [4]. This potentially reduces the congestion and, in the long run, possibly, an improved flow in the moving of the traffic is offered. This would, hence, save the commuters and businesses a great amount of time and fuel.
Moreover, the advent of AVs presents opportunities for enhancing transportation efficiency and sustainability. It is optimized with driving patterns and minimum stops and unnecessary accelerations to minimize fuel reduction and emission, thus contributing to clean air and a healthy environment [5]. In addition, the integration of AVs into shared mobility services and electric propulsion technologies is projected to be further sustainable in the environmental footprint within the transportation system.
This is besides behavior, which takes a critical course in shaping the impact of AVs in the transportation systems besides all these transformative possibilities. The broad range of AV behaviors influences several critical performance metrics such as travel time, queue length, delay, emissions, and overall safety [6]. Important in the effective integration of AVs with already-existing transport infrastructure, understanding the aggressive maneuvers as well as the implication of those behaviors, ensures that the full potential of AVs can be realized.
The widespread adoption of AVs is poised to significantly influence urban planning, public transportation, and employment within the driving sector. Cities may need to redesign roads and public spaces to accommodate AVs, potentially leading to reduced traffic congestion and more efficient land use. Public transportation systems could see increased efficiency and usage, contributing to a decline in privately owned vehicle numbers. The reduction in the number of human-driven vehicles will likely lead to fewer accidents, translating into lower healthcare costs and insurance premiums. Additionally, there will be a shift in employment as jobs related to driving decrease, necessitating workforce retraining and support.
As AVs become more prevalent, human drivers will need to adjust their driving behaviors. This adaptation includes developing trust in AV technology and learning to interact safely with AVs. The presence of AVs may lead to smoother traffic flows and fewer aggressive driving incidents. Over time, human drivers might become more accustomed to AVs'

predictable behavior, resulting in a more harmonious coexistence on the road. Moreover, shared mobility and reduced car ownership could become more common, further enhancing the efficiency and sustainability of transportation systems.
Not least, the fact that with the continued and ever-increasing spread of AV technology and adoption rates, it is high time that this is not exactly surprising since the broader aspects of the implications of different driving behaviors are considered. Incorporating AVs into the fabric of modern mobility systems, therefore, imposes complex questions on regulatory frameworks, infrastructure investment, and societal impacts in such a way that they'll need to be considered by transportation planners, policymakers, and their stakeholders. Endorse a collaborative atmosphere between stakeholders, industry, researchers, and policymakers, which would facilitate the coexistence of new-age vehicles i.e., autonomous vehicles with traditional forms of transport. We would be hoping to bequeath a new era of mobility that will make life way safer, efficient, and sustainable for all.

1.2 Importance of Autonomous Vehicles in Signalized Intersections

Autonomous vehicles (AVs) are poised to revolutionize modern transportation, offering a new paradigm in mobility, safety, and efficiency. The significance and impact of AVs in contemporary transport systems, particularly within the context of signalized intersections and their influence on travel time, queue length, delay, and speed, can be understood from several perspectives, each reflecting a distinct set of advantages and opportunities that contribute to their potential transformative role [8].
Economic Benefits: The high likelihood is that economically, within the signalized intersection limits, the AVs are likely to yield immense benefits. In this context, it guarantees the fact that efficiency and optimization driven into the operation of transport may convey some sort of savings in cost, reduced congestion, and improved productivity mainly improved traffic flow and reduction of delay at the junctions. This will be efficient along the supply chains of businesses and can be during operation [9, 10]. With improved transport and logistics coordination, businesses are likely to have improved efficiency in both supply chains and operations.
Social Inclusivity: AVs may, in fact, totally affect, if not within the wide purview of signalized intersections, impact or even revolutionize access to mobility for those that are restricted by various forms of disabilities or those whose level of age has brought about their driving ability reducing. AVs bring the potential to provide all members of society with greater inclusivity and independence in reliable, easy transportation solutions at all intersections. In that connection, AVs also have the potential to revolutionize public transport systems with reliable and convenient services that reduce the degree to which AV users rely on the private vehicle and, hence, be in a position of encouraging sustainable urban development [11, 12].
Safety Enhancements: Safety will continue to be a very critical part even in the signalized intersection environment, where AVs can help in reducing accidents caused by errors of human beings to a great extent. AVs, with their advanced sensing technologies and precise control systems, have the potential of reducing the frequency of collisions and overall intersection safety. AVs led to decreased accidents and injuries, especially at the intersections, by eliminating the driver's fatigue, distraction, and other factors peculiar to human beings [13].
Urban Planning and Optimization of Infrastructure: In the area of the signalized intersection, AVs open a window toward new opportunities for urban planning and efficient use of infrastructure. With coming improved connectivity and communication systems, such vehicles can maximize the utilization of road networks while minimizing traffic flow, to reduce congestion if not eliminated, at such cases junctions. Also, they lay a role in smart city development via their seamless integration with other upcoming

technologies of the Internet of Things (IoT) and Artificial Intelligence (AI), mainly in the management of traffic patterns and effectiveness of the intersection [14, 15].

Taken together, these represent a potential universe of AV impact that may be felt not just across the more confined study area of signalized intersections but across the whole of urban environments. The multifaceted benefits that they bring forth economic, improved access to mobility, safety, and efficiency are set to reshape the current state of transport systems, particularly at one of the critical nodes of these networks: signalized intersections. As AV technology continues to mature and gain universal acceptance, it is pertinent to embrace the opportunities they bring in an intersectional context and move together towards a smarter, safer, and more sustainable future.

1.3 Objective and Scope of the Review

The focus of this study is to discuss the effects of the identified driving behaviors cautious, normal, aggressive of the autonomous vehicle (AV) in the transportation system overall, and at specific signalized intersections. The review seeks to appreciate how the different modes affect some of the transportation key aspects, such as travel time, queue length, delay, and speed at intersections, all relevant to a detailed account of AV behavior within the domain.

This review will, in effect, critically and systematically investigate a targeted analysis of the state-of-the-art existing studies, reports, and case studies conducted on the effect of AV driving behaviors on transportation metrics within signalized intersections. It seeks to provide an all-inclusive analysis of how careful, moderate, and aggressive modes of driving affect traffic dynamics at signalized intersections, with clear emphasis on travel time, queue length, delay, and speed.

In addition, the review tries to bring out possible advantages and disadvantages that are associated with every driving mode within the perspective of the signalized intersections. Through the synthesis of existing literature with empirical evidence, the review derives some insights for transportation planners, policymakers, and stakeholders involved in the development and implementation of autonomous vehicle technologies at intersections.

2. Types of Autonomous Vehicle Behaviors

To exhibit a variety of driving behaviors in a continuum, from the most conservative to the most aggressive, based on the desired balance of safety and efficiency. This section is quite detailed and outlines a review of the different driving modes that would apply for AVs. Further, it elaborates on the characteristics of each, bringing not only to the fore what the implications these driving modes may have on transportation systems are but also delving deeper into their implications on society. To understand the varied driving modes that AVs are capable of with full autonomy, it is key to appreciate the disruptive revolution they are unleashing in the world of transport. Deeper exploring these driving modes, what did we find? Yes, further valuable insight into the possibilities that will arise in case of independent vehicles and the limitless potential of autonomous vehicles [17-19].

2.1 Overview of Driving Modes

Autonomous vehicles typically offer multiple driving modes, each influencing how they navigate roads and interact with traffic. The three primary driving modes are as follows:

In Cautious Mode, AVs prioritize safety by taking extra precautions to avoid collisions and ensure smooth driving. They maintain larger following distances, reduce speed in uncertain situations, and are more conservative at intersections. This style of driving is characterized by low speed, huge following distance, conservative decisions, and high sensitivity to hazards. While the behavior makes driving safe, it generally results in long traffic delays, high queue lengths, and low overall efficiency [4].

Thus, Normal Mode would mean balanced behavior like the one an average human driver exhibit. In this mode, the AVs will observe traffic rules, go at average speeds, and keep average following distances without so much caution or aggression. It has moderate speeds, standard following distances, medium decision speeds, and flexible adaptability to traffic conditions as some of its features. Normally, the balance between efficiency and safety is held under normal mode [4].

Aggressive Mode adopts a more assertive style of driving, seeking efficiency and minimization of trip time. AVs in this mode will drive faster, get a shorter headway, and have quicker decision-making. They would also have a lower tendency to give way to others on the road. However, with potential considerations for safety, such actions could lead to an increase in the volume of traffic and reduce travel time, while an increased volume of traffic and greater potential for accidents and other traffic hazards may result [4].

3. Impact on Intersection Performance

3.1 Impact on Total Travel Time

The study by [4] showed evidence of the effect of the different driving behaviors of autonomous vehicles (AVs), especially their differences in logic, on the total travel time (TTT) at signalized intersections. The following are some key points about the results of the study, illuminated by the varied rates of penetration and driving behavior affecting the efficiency of intersections and the flow of traffic.

The cautious driving logic applied to AVs will make them prioritize safety over speed, thus leading to a longer travel time. This is slow in acceleration and deceleration to avoid sudden speed changes. A 100% penetration rate of cautious AVs increases the total travel time by 1.15% compared to the human-driven case. However, AVs with normal logic balance cautious and aggressive actions by yielding total travel times between that of an AV with cautious logic and an AV with aggressive logic, as shown in Fig. 1.

The AVs use an aggressive logic that keeps the gap with the surroundings closer and reduces the time needed for reaction at intersections, which results in a more efficient flow of the traffic. That way, such AVs would be able to communicate with other kinds of vehicles and, through the modern means of communication, including vehicle-to-vehicle (V2V) communication, reduce bottlenecks and unnecessary stops. This is one key reason that, at 100% penetration, the all-knowing trip rate is still 14.26% signifying enormous reduction from human-driven vehicles and cautious logic, as shown in Fig. 1. To use the strongest and most advanced version of the humanizer with a 100% human result as shown in Fig. 1.

Further analysis of the mixed scenarios, where AVs of different driving logics coexist, shows higher total travel time with respect to the normal and all-knowing logic. The logic in any area of the traffic resulted in higher TTT due to the random nature of mixed traffic likely causing inconsistency and inefficiency.

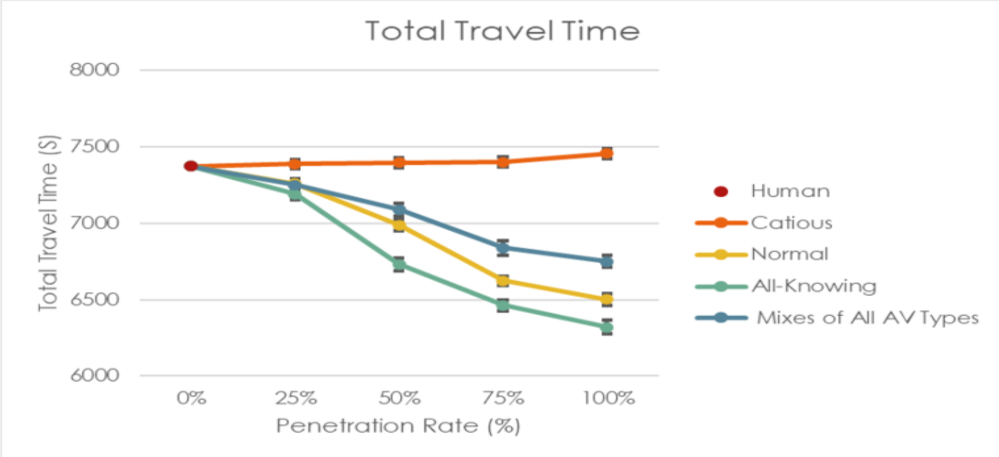

Fig.1 Total travel time vs AVs penetration rate [4]

The present study outlines simulations in five scenarios to evaluate the connected and automated vehicle (CAV) behaviors affecting the travel time average at signalized intersections. These included scenarios with 100% conventional vehicles, mixed traffic 50% conventional, 50% CAV all-knowing, 100% CAVs cautious, 100% C. On average, all the 50 travel times considered showed that the CAV scenarios generally improved intersection operations by reducing average travel time. The average travel time was specifically reduced in Scenario 4 (100% CAVs Normal) between 4%-14% due to the balanced behavior of normal CAVs and further reduced in Scenario 5 (100% CAVs All-knowing) between 8%-25% because all-knowing CAVs behaved aggressively with advanced communication capabilities. Overall, these findings suggest the higher penetration rates of CAVs, particularly with driving logic, would be assertive to enhance intersection efficiency in reducing average travel time, with mixed scenarios likely to be offered by intermediate results.

3.2 Impact on Queue Length

In A [4], the effect of the various automated vehicle (AV) driving behaviors on the queue length at signalized intersections revealed that for penetration rates of AVs and the behaviors, which are given in Fig. 2, there is a difference. This cautious logic of a safety-constrained AV increases queue lengths, since at 100% penetration, they have on average, a 3.5% increment compared to human-driven vehicles (HVs). Conversely, the balanced driving behavior with Normal Logic in AVs reduced the queue length by 3.3% on average compared to HVs, where 100% penetration was used, improved Signalized Intersections efficiency with the reduction in congestion. The All-Knowing (Aggressive) Logic, aggressive driving behavior, and, therefore, advanced communication capabilities experienced the lowest queue lengths due to their penetration rate of 100%, hence an average decrease of 5.5% compared with the HVs, improved traffic flow, and reduction in congestion. Mixed Scenarios, in which various AV types were considered, have also resulted in the reduction of queue lengths. Thus, they reveal that possibly there is some synergy possibility for different AV combinations at influence intending an improved intersection performance. The study further noted that the change in QL trends became more drastic after a 50% penetration rate of all AV types. Therefore, this goes on to show that higher AV penetration rates in traffic may result in much more amplified changes in queue lengths and hence overall intersection efficiency.

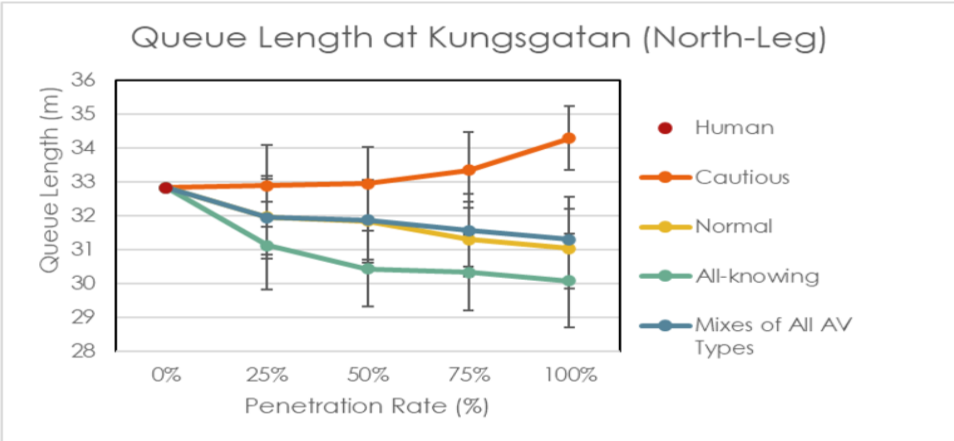

Fig.2 Queue length at Kungsgatan (North-leg) vs AVs penetration rate [4]

The outputs from [4] clearly underline the major role of driving behaviors and penetration rates of autonomous vehicles (AVs) towards the queue lengths at signalized junctions. More assertive and coordinated AV behaviors, such as the all-knowing logic, shorten the queues, but the cautious ones tend to lengthen them as shown in Fig.3. In this case, normal logic assumes the role of a balancer, ensuring not only that the queues are shortened but also that there is safety. The above mixed scenarios have a positive impact on performance within the intersection. It therefore shows how the gradual increase of AVs in a scenario is beneficial to efficiency in traffic. Furthermore, the study presented the impacts of various connected and automated vehicle (CAV) scenarios on the queue length at an intersection, in which they simulated five scenarios of CAVs representing different driving behavior [20]. The study found that for those cases where CAV behavior was normal or omniscient, the queue was reduced compared to conventional vehicles' queue length for the specific scenario. However, in cases where the CAV behavior was cautious, the queue length exceeded that of conventional vehicles. This seemed to have another impact from another set of CAV behaviors in relation to intersection congestion.

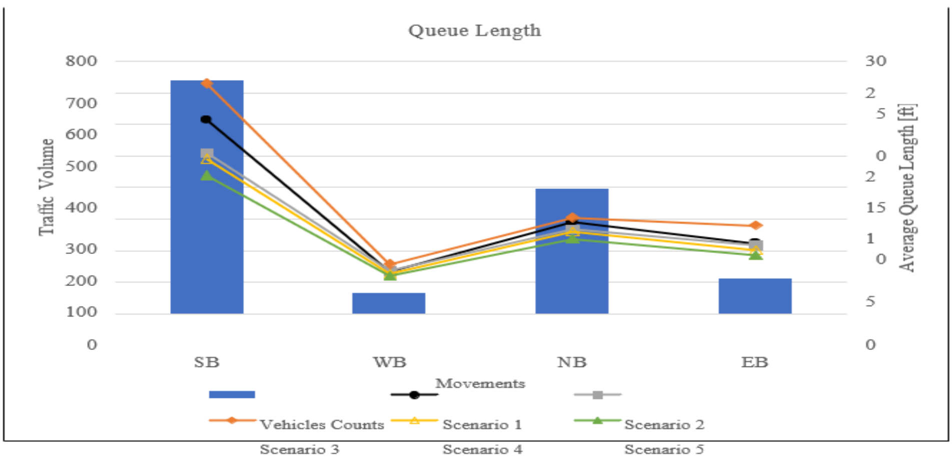

Fig.3 Queue length at Kungsgatan (North-leg) vs AVs penetration rate [20]

This tendency is the same as pointed out in [20], which emphasizes the findings that CAVs (connected and automated vehicles) being cautious increase the queue length because of the safety-focused approach speed and rate. On the other hand, CAVs (normal and all-knowing) promote less queue length, which is part of the optimized approach for a safer and more efficient traffic flow at signalized intersections. Furthermore, the mixed scenarios of ConVeh and CAV also suggest potential for improvement in intersection performance regarding the queue length. A study [21] indicated that in 100% deployment of autonomous vehicles, queue length with transition from regular vehicle flow to autonomous vehicle flow including CAVs of both aggressive and connected types has remarkably reduced at all levels of traffic density. Especially at medium and high traffic volumes, CAVs, specifically the connected ones, posted the most eminent reductions in queue length, indicating efficiency in managing even higher traffic densities. These reductions are particularly marked at medium-level traffic volumes and hence suggest that CAVs can be effective within moderately congested urban areas. This evidence fully underscores the potential for full AV implementation to improve traffic flow and reduce congestion at problem intersections.

3.3 Impact on Delay

In [4], the authors related to one interesting finding concerning the effect that various autonomous vehicle (AV) driving behaviors have on the average delay at signalized intersections and showed that there are indeed variations affected by AV behavior. Cautious Logic results in the highest average delay since it encourages conservative driving behavior and, therefore, more congestion and delays will be encouraged, while All-Knowing (Aggressive) Logic results in the lowest average delay since rapid response times and driving aggressively are used. This demonstrates normal logic with intermediate effects on delay, a pattern where a 25% AV penetration rate both increases and decreases with increased penetration rates. As the penetration of AVs increases, the delay starts reducing, notably by the all-knowing logic: reduction of delays is by advancing communication and aggressive driving. This study reiterates the huge role that driving logic and penetration rates play to determine average delay at signalized intersections, basically pointing out to the necessity of advanced driving logic in reducing delays and enhancing efficiency. Furthermore, [20] considered the impact of several connected and automated vehicle (CAV) scenarios on a series of performance metrics, including queue delay. The performance metrics improved in almost every movement, except in some turns. Additionally [21] investigated the effects of autonomous vehicles on the performance of the intersection under various mixed traffic conditions, pinpointing that the delay times receive significant decreases even with partial AV implementation. This can show that the connected autonomous vehicle model would be preferable to alleviate intersection delays, which would be 5.4 times better than the conventional ones, with special attention given to moderate levels of traffic volumes. Hence, the findings underscore the significant role of AVs in improving intersection efficiency, joined with optimizing signalized operation with growing penetrations of AVs into the urban traffic system.

3.4 Impact on Speed

Average speed at a signalized intersection is a critical metric for assessing traffic performance, as it reflects the efficiency of traffic flow and the behavior of vehicles at intersections. The study by [4] explores the impact of various driving behaviors and penetration rates of autonomous vehicles (AVs) on average speed.

Fig. 4 shows the trends in average speed for different scenarios and driving logic. The study reveals an inverse relationship between average speed and driving logic, with cautious AVs exhibiting the lowest average speed and all-knowing AVs showing the highest average speed.

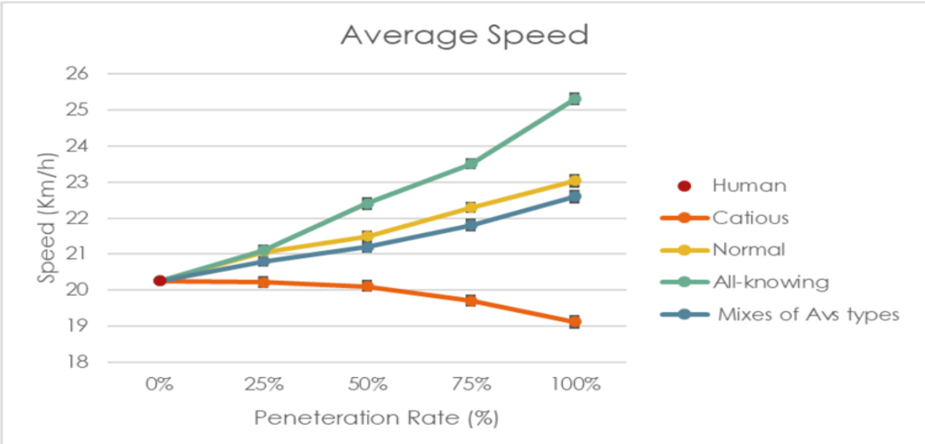

Fig.4 Average speed vs AVs penetration rate [4]

In scenarios with 100% cautious autonomous vehicle (AV) penetration, the mean speed reduces by 6% compared to the base (100% human-driven vehicles) scenario, as cautious AVs realize a conservative approach that, therefore, results in slower traffic flow. On the other hand, the much more safety-conscious human drivers result in up to a 29% reduction in traffic speed at 100% penetration. On the other hand, all-knowing AVs at 100% penetration had the average traffic speed increased by 25%, pointing towards a significant improvement in efficiency of traffic flow. Normal AVs strike a balance at. The scenarios of mixed also showed speed gains of 11.5% with 100% AV penetration, reflecting varied AV behaviors that cause an enhancement in traffic flow. As the AV penetration increases, human-driven vehicles will reduce, allowing AVs to do the task of traffic flow, mostly past 50% penetration. However, with lower rates of penetration, AVs align the speeds of the vehicles driven by humans for safety and efficiency while still maintaining a natural driving experience, natural traffic flow, and consistency. Overall, behavioral driving and penetration rates have significant implications for speed at signalized intersections and will guide future strategies for AV integration and intersection optimization.

3.5 Impact on Emissions and Fuel Consumption

the environmental impacts of aggressive heavy goods vehicle (HGV) platoons compared to human-driven HGVs at signalized intersections. The findings revealed that aggressive HGV platoons generally resulted in lower emissions and fuel consumption as shown in Fig. 5 while improving flow and reducing delays, especially under high traffic volumes. These results suggest that incorporating aggressive HGV platoons into urban traffic systems could enhance intersection efficiency and reduce environmental impacts.

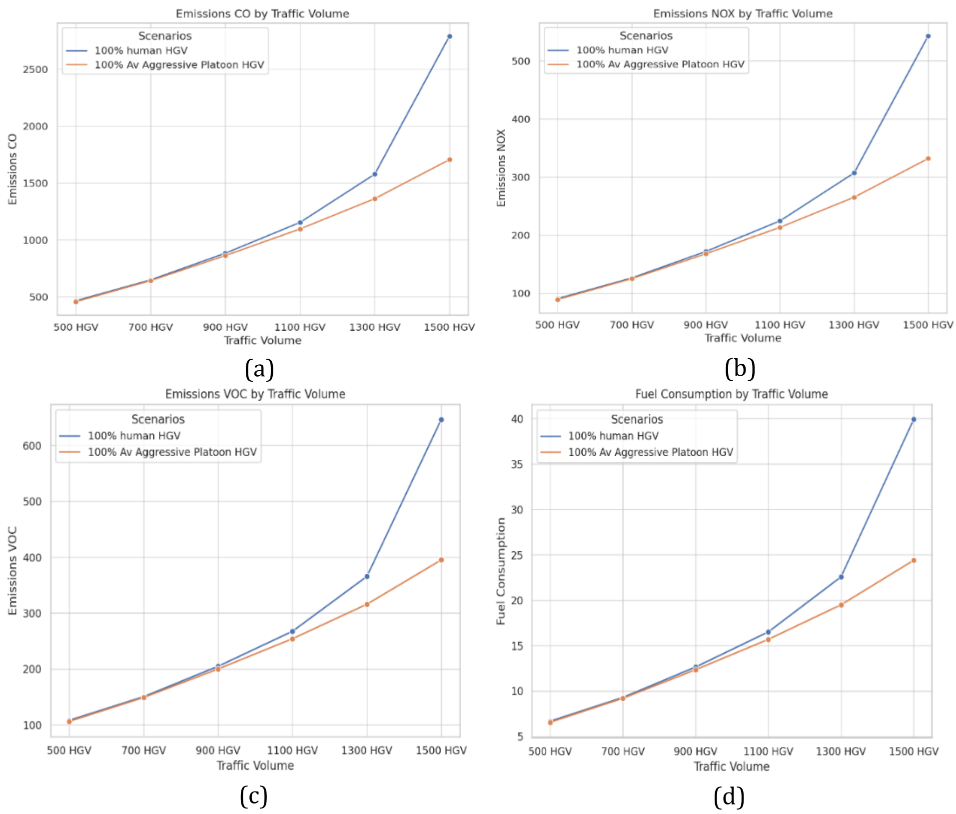

Fig. 5 (a) CO Emissions, (b) NOx Emissions, (c) VOC Emissions, (d) Fuel Consumption [23]

4. Conclusions and Future Directions

The exploration of autonomous vehicle (AV) driving behaviors at signalized intersections reveals complex dynamics that impact key transportation metrics like travel time, queue length, delay, and speed. This analysis offers valuable insights into how AVs interact with existing traffic systems and the implications for future urban mobility.

4.1 Key Findings and Insights

The results clearly point to important implications for the future transportation system, like the potential of integrating autonomous vehicles (AVs) into a reduction in travel time, unblocking of traffic, and an increase in the general system efficiency. However, the penetration rate of AVs and the behavior of the drivers matter significantly for the success. If high penetration is reached by knowledgeable and cautious AVs, the traffic flow will optimize, though strategies for proper management have to be in place concerning the increased lengths of queues and congestion. Some will have to be essential infrastructure adaptations, regulatory adjustments, and advancements in smart city technologies. Several studies, hence, call for more investigation to understand the actual impact of AV through longitudinal studies, safety assessment, environmental evaluations, and human factor investigations. If such research gaps are filled and proper precautions are taken, it promises safer, efficient, and sustainable mobility for all.

4.2 Implications for Future Transportation Systems

The findings therefore highlight some potential benefits from the implementation of Autonomous Vehicles (AV) in the transportation system, such as travel time savings, improvements in traffic flow, and increments in safety, among others. However, these benefits will depend much on the driving behaviors of AV and penetration rates. The flow of traffic with high penetration would be the best if an AV fleet were knowledgeable and cautious. On the other side, it would make other strategies mandatory to cut delays and congestion. The future transportation systems, in turn, would require these to be modified and used for a variety of purposes the AVs would need. The adaptations would be changes in infrastructure and regulation to evolutionary policy frameworks around safety, efficiency, and equitable access. This shift will guarantee opportunities in which "smart cities" can develop, which will facilitate the building of integrated systems that will be supportive of "autonomous driving" and "advanced communications technologies," enhancing more efficient and sustainable urban transportation networks. As such, it is important that cities and communities make prior planning for and addressing these implications so that they can fully harness the potential of autonomous mobility while at the same time building safer and more sustainable transportation networks for all.

4.3 Recommendations for Further Research

Further inquiry would humanly understand the full impact of autonomous vehicles (AVs) on transportation systems and optimal incorporation methods. Major recommendations also include conducting longitudinal studies to track AV impacts over time. These will be very important studies for a change in driving behavior and their effect on transportation systems. Further studies will also conduct safety and risk assessment of different AV driving behaviors, ensuring that the regulatory framework is developed for their safe integration within the current traffic systems. It will be important to reconsider the effect that AVs would have on the environment and fuel emissions. Since it will be impossible to avoid such an effect on the environment, subsequent studies need to manage the carbon footprint effectively. Further research on human factors and user acceptance has shown that what is most important is human drivers' interaction with AVs and that the assessment of public perception of acceptance is important to anticipate challenges that may help them succeed in the transition to autonomous mobility. Therefore, it ensures these recommendations work towards furthering the aims of this research, which includes integrating autonomous vehicles into the transportation systems and thereby promoting a future that is safe, efficient, and sustainable.

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