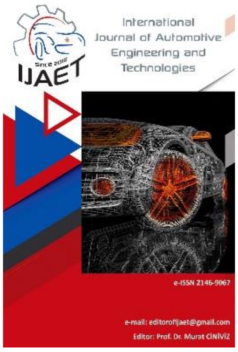
e-ISSN: 2146 - 9067

International Journal of Automotive Engineering and Technologies

journal homepage:
https://dergipark.org.tr/en/pub/ijaet



Original Research Article

Comparative conflict analysis of human-driven and autonomous vehicles at signalized intersections

Mustafa Albdairi[1*], Ali Almusawi[2], Syed Shah Sultan Mohiuddin Qadri [3]

[1,* 2] Department of Civil Engineering, Çankaya University, Ankara, Türkiye.
[3] Department of Industrial Engineering, Çankaya University, Ankara, Türkiye.

ARTICLE INFO

Orcid Numbers

1. 0009-0002-6673-363X
2. 0000-0002-4507-2492
3. 0000-0002-2950-3993

Doi: 10.18245/ijaet.1523772

* Corresponding author
c2290007@student.cankaya.edu.tr

Received: Jul 28, 2024
Accepted: Oct 16, 2024

Published: 31 Dec 2024

Published by Editorial Board Members of IJAET

ABSTRACT

Integrating autonomous vehicles (AVs) into urban traffic systems presents both opportunities and challenges, especially at signalized intersections. This study offers a comparative conflict analysis of human-driven vehicles and AVs at a busy four-legged signalized intersection in Balgat, Ankara, Turkey. Using PTV VISSIM for detailed traffic simulation, the research assesses the effects of various AV driving styles - cautious, normal, aggressive, and a mix of all three - at different penetration rates (25% to 100%), alongside standard human-driven vehicle scenarios. The Surrogate Safety Assessment Model (SSAM) is employed to analyze safety implications both before and after intersection design calibration. The findings demonstrate notable differences in conflict points between human-driven and AV scenarios. Before calibration, cautious AV behaviors result in higher conflict points due to increased queuing, while aggressive behaviors reduce conflicts through more efficient traffic flow. Human-driven vehicles exhibit varied conflict levels based on driver behavior. After calibration, significant improvements are observed across all scenarios, with aggressive AVs achieving the greatest reduction in conflict points. This study highlights the potential for AVs to improve intersection safety and efficiency when appropriate design calibration measures are implemented.

Keywords: Autonomous Vehicles, Signalized Intersections, Traffic Simulation, Conflict Analysis, Intersection Design Calibration

1. Introduction

Autonomous vehicles (AVs) are rapidly transforming urban transportation, offering both promising advancements and significant challenges, particularly at signalized intersections (1,2). These intersections are critical nodes in urban traffic management, where the integration of AVs can significantly impact traffic flow and safety (3).

Understanding the dynamics of AVs at these intersections is crucial for developing strategies to optimize their performance and mitigate potential conflicts (4).

As AVs are integrated into existing traffic systems, they introduce complexities that stem from the interaction of both AVs and human-driven vehicles. Signalized intersections, where vehicles from multiple directions converge, are uniquely challenging for AVs (5). Managing this complexity involves interpreting traffic signals, navigating human drivers' unpredictability, and adhering to right-of-way rules.

Moreover, the varied driving behaviors of AVs - ranging from cautious to aggressive - further complicate their interaction with human drivers and other AVs (6). Cautious AVs may prioritize safety and adhere strictly to traffic laws, which can lead to increased queuing and potential delays (7). Conversely, aggressive AVs aim to minimize travel time by taking advantage of gaps in traffic, which may improve flow but also increase the risk of conflicts (8).

The presence of mixed traffic conditions, where human-driven vehicles and AVs share the road, adds another layer of complexity. Human drivers exhibit a wide range of behaviors and decision-making processes that can be unpredictable, making it challenging for AVs to accurately anticipate and react to their actions. This unpredictability can lead to conflicts, such as sudden braking or swerving to avoid collisions. Additionally, AV penetration rates, defined as the proportion of AVs in the overall traffic mix, vary across scenarios, impacting traffic dynamics and the effectiveness of management strategies (9).

Understanding the interaction between AVs and human-driven vehicles at signalized intersections is not only essential for improving traffic efficiency but also for ensuring safety. Studies have indicated that while AVs have the potential to reduce traffic accidents, the transitional phase where both AVs and human-driven vehicles coexist presents significant safety challenges. This study aims to address these challenges by conducting a comprehensive conflict analysis, which will provide insights into how different AV behaviors and penetration rates impact safety and efficiency at signalized intersections. By doing so, it seeks to inform the development of strategies and policies that can facilitate the seamless integration of AVs into urban traffic systems, ultimately leading to safer and more efficient intersections.

The primary problem addressed in this study is the analysis of conflict points associated with the interaction between AVs and human-driven vehicles at signalized intersections. Conflicts, such as near-crashes or sudden braking incidents, can provide valuable insights into the safety and efficiency of traffic systems incorporating AVs. This study seeks to fill the gap in existing research by focusing on conflict analysis, which is a less explored but vital aspect of AV integration in urban traffic.

The objectives of this study are threefold: first, to evaluate the impact of different AV driving behaviors (cautious, normal, aggressive, and a mix of these) on conflict points at a busy four-legged signalized intersection; second, to compare these scenarios with those involving human-driven vehicles; and third, to assess the effects of intersection design calibration on reducing conflict points. By addressing these objectives, the study aims to provide practical recommendations for enhancing traffic safety and efficiency in mixed traffic environments.

2. Literature Review

The integration of autonomous vehicles (AVs) into urban traffic systems has sparked considerable research interest, particularly in understanding how these vehicles interact at signalized intersections. One major area of focus has been the conflict analysis between AVs and human-driven vehicles at these critical junctions. Signalized intersections are complex environments where vehicles from multiple directions converge, necessitating advanced control strategies to ensure smooth and safe traffic flow.

The integration of Connected and Automated Vehicles (CAVs) significantly enhances safety at intersections. (10) examined the impact of CAVs on signalized and unsignalized intersections using the SUMO simulator. Their findings indicate that CAVs reduce conflicts and rear-end collisions, particularly at higher penetration rates, by minimizing human error.

The study utilized car-following models such as Krauss, IDM, and CACC, with CACC notably decreasing rear-end conflicts. These results highlight CAVs' potential to improve road safety and traffic efficiency through advanced driving systems and V2V communication.

(11) Investigated the safety benefits of Automated Speed Advisory Systems (SAS) at signalized intersections. Their study demonstrated that SAS vehicles reduce collision risks and improve driving behaviors by enhancing time to collision and deceleration rates. The simulations showed that SAS vehicles, especially at higher market penetration rates, significantly lower rear-end collision risks. The research also explored various scenarios, including different ranks of SAS vehicles and lane-changing possibilities, confirming SAS's positive impact on intersection safety.

The study by (12) proposed a safety-aware and data-driven predictive control framework for CAVs at signalized intersections in mixed traffic environments. Their approach prioritizes collision avoidance with human-driven vehicles during signal phases, using a recursive least squares algorithm to approximate driving behavior. The effectiveness of the safety-aware control framework was validated through numerical simulations and robust analysis, demonstrating its potential to enhance intersection safety by deriving optimal trajectories for CAVs.

Hashmatullah and Antoniou (13) conducted a simulation-based impact assessment of AVs in urban networks using microscopic traffic models. Their study utilized a particle swarm optimization algorithm to calibrate the model and assess the influence of AV penetration on both safety and traffic efficiency. The results indicated that higher AV penetration rates significantly enhance safety; however, the impact on traffic efficiency was inconsistent. While AVs may slightly increase the average network travel time, the overall safety improvements make their integration beneficial.

A study by Kim, Cho, and Lee (14) explored a novel method using traffic accident data to identify pilot zones for AV safety testing. The approach utilizes a CNN + BiGRU model for accident classification, achieving remarkable accuracy with 100% recall and 99.5% classification accuracy. By employing outlier detection and DBSCAN clustering, the study successfully identified 562 AV-like accident cases from a total of 798. This method provides an efficient solution for selecting pilot zones, enabling effective AV safety validation while potentially reducing testing costs. The findings underscore the importance of using real-world data to enhance AV deployment safety.

However, these studies highlight the broad safety benefits of automation but do not delve into how different AV driving behaviors—such as cautious, normal, and aggressive—may impact these outcomes differently. This study aims to fill this gap by focusing on the distinct driving behaviors of AVs—cautious, normal, and aggressive—and analyzing their respective impacts on traffic conflicts at signalized intersections. By investigating how each of these behaviors affects traffic dynamics and safety outcomes, this research provides a more detailed and behavior-specific understanding of AV integration, offering insights that can inform both traffic management strategies and AV policy development. This focus on behavioral differentiation is what distinguishes our approach from prior studies, offering new insights into the complexities of AV behavior in urban traffic systems.

Figure 1 Geographical Layout of the Signalized Intersection in Balgat, Ankara.

3. Methods

3.1. Study location

The research was conducted at a busy four-legged signalized intersection located in Balgat, Ankara, Turkey, which is shown in Figure 1. This intersection, situated at the crossroads of Kızılırmak and Ufuk Ünv. Cd No:18, 06520 Çankaya/Ankara, features four lanes for both northbound and southbound traffic, and three lanes for both eastbound and westbound traffic. The selected site provides an excellent real-world scenario with high traffic density, making it ideal for evaluating the effects of Autonomous Vehicles (AVs) on traffic flow and behavior.

3.2. Research methodology overview

To enhance clarity and provide a comprehensive understanding of the research process, the methodology is summarized in the flowchart as shown in Figure 2. The research begins with Data Collection, where the focus is on gathering Traffic Volume Data and Speed Distributions. These datasets are essential for building accurate simulation models.

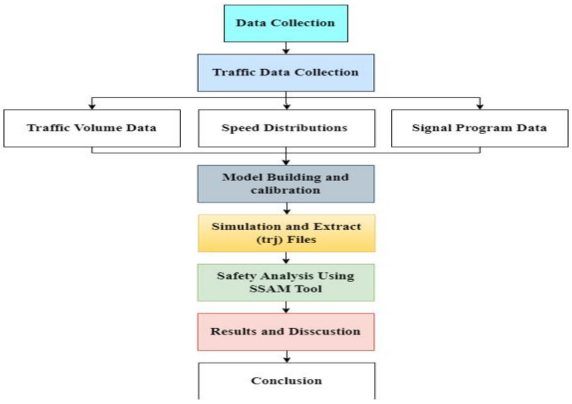


Figure 2 Flowchart of research methodology.

In the Model Building and Calibration phase, the collected data are used to construct a realistic simulation environment and ensure the model reflects real-world conditions accurately. After calibration, simulations are run, and trajectory (trj) files are extracted for analysis.
The Safety Analysis is then conducted using the Surrogate Safety Assessment Model (SSAM) tool, which processes the trajectory files to evaluate potential conflicts and safety metrics. Finally, the results from the safety analysis are interpreted and discussed in the Results and Discussion section, leading to the study's Conclusion.
This systematic approach ensures that the research is both rigorous and transparent, facilitating reproducibility and validation.

3.3. Traffic volume

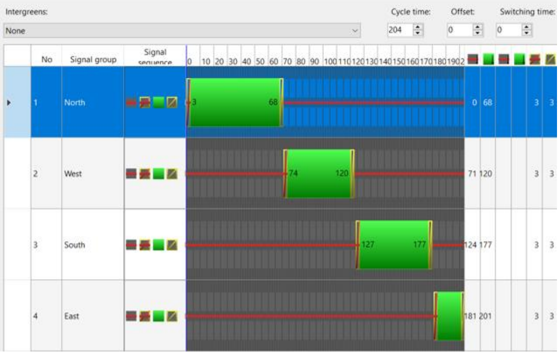
The traffic volume data was collected through video analysis conducted during peak morning hours from 7:00 to 8:00 AM, as shown in Table 1. The total recorded traffic volume during this period was 5386 vehicles.

Table 1. Traffic movements recorded at the signalized intersection

Direction	Total Vehicles	Right Turn	Straight	Left Turn
N	1793	225	679	889
E	1033	814	157	62
S	1508	244	1228	36
W	1052	28	132	892

3.4. Signal program timing

In the context of signal timing at the studied intersection, Figure 3 illustrates the sequence of green, red, and amber light durations for each traffic direction. Detailed observations were made using video recordings to extract these traffic control parameters. The cycle time, set at 204 seconds, governed the signal sequence. As shown in Figure 3, the green light durations were observed to be 65 seconds for the northbound direction, 46 seconds for the eastbound direction, 50 seconds for the southbound direction, and 19 seconds for the westbound direction. The red and amber light durations were uniformly maintained at 3 seconds each across all directions. These signal timings were meticulously documented to reflect the actual conditions recorded during the video analysis.


Intergreens: None
Cycle time: 204
Offset: 0
Switching time: 0

No	Signal group	🟥	🟩	🟥	🟩	▨	▨
1	North	0	68			3	3
2	West	71	120			3	3
3	South	124	177			3	3
4	East	181	201			3	3

Figure 3 Signal Program Timing of the Signalized Intersection in Balgat, Ankara.

3.5. Desired speed distributions

In assessing the speed distribution for human-driven vehicles at the specified intersection, Figure 4 illustrates the results of the speed observations conducted. This analysis focuses on vehicles traveling north and south during green signals, where the speeds of 20 vehicles were measured over a 150-meter distance using a stopwatch. As depicted in Figure 4, the results show that 40% of the vehicles traveled at speeds between 20 km/h and 27 km/h, 42.5% between 28 km/h and 36 km/h, and 17.5% between 36 km/h and 39 km/h.

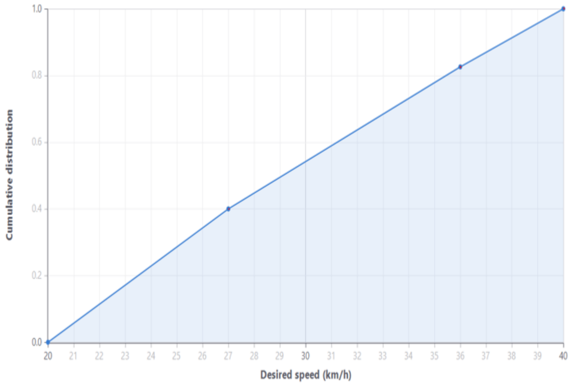


Figure 4 Speed Distribution of Human-Driven Vehicles.

Figure 5 illustrates the speed characteristics of autonomous vehicles (AVs) in the simulations conducted. Whether operating independently or in mixed traffic with human-driven vehicles, AVs consistently maintained speeds between 27 km/h and 31 km/h.

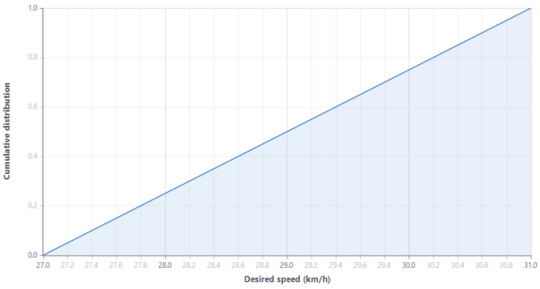


Figure 5 Speed Distribution of Autonomous Vehicles.

3.6. Car-following and lane change models

Table 2 presents the specific driving parameters defining three distinct AV driving behaviors analyzed in this study:

- Cautious AVs: Emphasized safety with a 1.50-meter standstill distance and a 1.5-second gap time, promoting conservative driving.
- Normal AVs: Balanced safety and efficiency, maintaining a 1.50-meter standstill distance but reducing the gap time to 0.9 seconds, with acceleration from standstill set at 3.50 m/s².
- Aggressive AVs: Adopted a closer 1.00-meter standstill distance, a 0.6-second gap time, and higher acceleration of 4.00 m/s², indicating more assertive driving.

Human driving behavior was simulated using the Wiedemann 74 model, which included an average standstill distance of 2.00 meters, an additive safety distance of 2.00 meters, and a multiplicative safety distance of 3.00 meters to reflect realistic driver responses and variability.

Table 2. Parameters for av car following models.

Parameter	Cautious	Normal	Aggressive
Standstill distance	1.50 m	1.50 m	1.00 m
Gap time distribution	1.5 s	0.9 s	0.6 s
‘Following’ distance oscillation	0.00 m	0.00 m	0.00 m
Threshold for entering ‘Following’	-10.00	-8.00	-6.00
Negative speed difference	-0.10	-0.10	-0.10
Positive speed difference	0.10	0.10	0.10
Distance dependency of oscillation	0.00	0.00	0.00
Oscillation acceleration	0.10 m/s^2	0.10 m/s^2	0.10 m/s^2
Acceleration from standstill	3.00 m/s^2	3.50 m/s^2	4.00 m/s^2
Acceleration at 80 km/h	1.20 m/s^2	1.50 m/s^2	2.00 m/s^2

The lane change model parameters were adjusted for different AV driving behaviors and human drivers to simulate realistic driving scenarios. Advanced merging was enabled for all vehicle categories, while cooperative lane change was activated only for AVs. The safety distance reduction factor varied, with AV cautious at 1.00 meters, AV normal at 0.60 meters, AV aggressive at 0.75 meters, and human drivers at 0.60 meters. Minimum clearance was set at 1.00 meters for AV cautious and 0.50 meters for the other modes. The maximum deceleration for cooperative braking was -2.50 m/s² for AV cautious, -3.00 m/s² for AV normal, -6.00 m/s² for AV aggressive, and -3.00 m/s² for human drivers. (17)

The lane change model parameters were adjusted for different AV driving behaviors and human drivers to simulate realistic driving scenarios. Advanced merging was enabled for all vehicle categories, while cooperative lane change was activated only for AVs. The safety distance reduction factor varied, with AV cautious at 1.00 meters, AV normal at 0.60 meters, AV aggressive at 0.75 meters, and

human drivers at 0.60 meters. Minimum clearance was set at 1.00 meters for AV cautious and 0.50 meters for the other modes. The maximum deceleration for cooperative braking was -2.50 m/s² for AV cautious, -3.00 m/s² for AV normal, -6.00 m/s² for AV aggressive, and -3.00 m/s² for human drivers.

3.7. Intersection design calibration

Figure 6 illustrates the real-world queuing behavior observed for the east and westbound lanes during the calibration process. Initially designed with two lanes, the observed traffic volumes required an adjustment to three lanes in the simulation model to better reflect actual traffic conditions.

Figure 6 Real-world Vehicle Queuing Scenario in East and West Bound Lanes. (18)

Additionally, given the high traffic volume, it was determined that lane changes should be restricted but still allowed at exit links as illustrated in figure 7. To achieve this, each lane was modeled as a separate link for each direction. This approach aligns the simulation more closely with observed traffic behaviors, enhancing the accuracy of the model.

Figure 7 Intersection design calibrated for no lane changes: each lane as a separate link.

3.8. Conflict points analysis

Figure 8 illustrates the conflict analysis process used in this study, highlighting the identification and recording of conflict points using VISSIM's built-in conflict analysis and the Surrogate Safety Assessment Model (SSAM) tools. The primary data obtained from the simulation included the number of crossing conflicts, rear-end conflicts, and lane-change conflicts. These conflict points were meticulously analyzed to assess traffic safety. Additionally, the mean time-to-collision (TTC) was calculated to provide further insights into the severity of potential conflicts. The data was analyzed to compare the total number of conflicts and the mean TTC across different scenarios, allowing for an assessment of how various AV behaviors and penetration rates affect traffic safety at intersections. This comparison provided valuable insights into the influence of AVs on intersection safety.

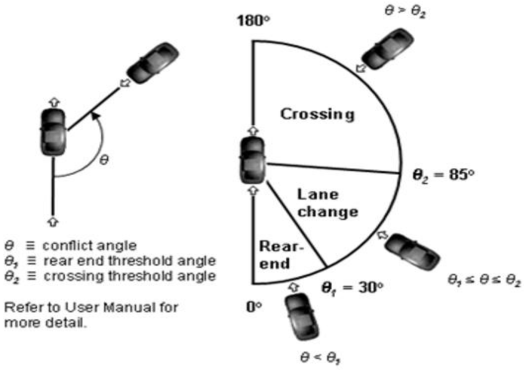


Figure 8 SSAM Angles Used for Analysis. (13)

3.9. Scenarios overview

Table 3 presents the 21 scenarios examined in this study, which investigate the interactions between human-driven and automated vehicles at intersections. These scenarios explore various AV behaviors, including aggressive, normal, and cautious, to capture the diverse dynamics of real-world traffic. This comprehensive approach ensures that the full range of potential AV impacts on traffic flow and safety are thoroughly evaluated.

Table 3. Overview of Autonomous Vehicle Scenarios

Scenarios	Cautious	Normal	Aggressive	Human
1	0%	0%	0%	100%
2	25%	0%	0%	75%
3	0%	25%	0%	75%
4	0%	0%	25%	75%
5	0%	0%	0%	75%
…	…	…	…	…
21	25%	25%	25%	25%

4. Results and Discussion

4.1. Impact of AV on conflicts point before calibration

The impact of AVs on conflict points was evaluated by comparing different AV behaviors and penetration rates before and after calibrating the intersection design.

Various types of conflicts, such as crossing conflicts, rear-end conflicts, lane-change conflicts, total conflicts, and Mean Time to Collision (TTC), were analyzed to determine how the integration of AVs influences safety at signalized intersections.

Figure 9 illustrates the number of crossing conflicts observed before and after calibration at the intersection. Initially, the intersection design resulted in higher crossing conflicts, particularly with cautious AV behavior. With 100% human-driven vehicles, there were 31 crossing conflicts. When cautious AVs were introduced at penetration rates of 25%, 50%, 75%, and 100%, the crossing conflicts decreased to 27, 7, 12, and 1, respectively. Normal AV behavior exhibited crossing conflicts of 15, 18, 8, and 1 at the same penetration rates. In contrast, aggressive AV behavior recorded 21, 10, 7, and 0 crossing conflicts. These results indicate that cautious and normal AVs can significantly reduce crossing conflicts, particularly at higher penetration rates.

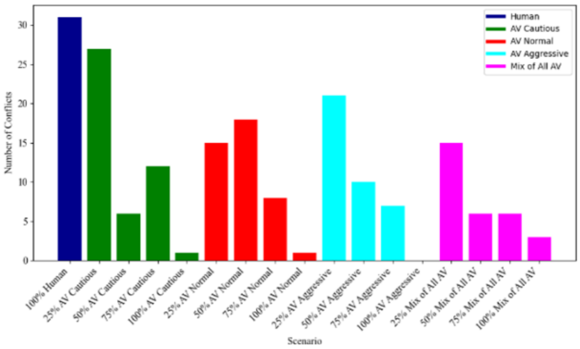


Figure 9 Crossing Conflicts for Different AV Behaviors and Penetration Rates Before Calibration.

Figure 10 illustrates the variation in rear-end conflicts across different AV behaviors. With 100% human-driven vehicles, there were 49 rear-end conflicts recorded. When cautious AVs were introduced at penetration rates of 25%, 50%, 75%, and 100%, the number of rear-end conflicts increased to 41, 57, 66, and 80, respectively. Normal AV behavior exhibited rear-end conflicts of 36, 52, 54, and 50 at the same penetration rates. In contrast, aggressive AV behavior recorded 50, 70, 97, and 96 rear-end conflicts. These findings suggest that cautious AVs tend to increase rear-end conflicts, while normal and aggressive AVs show mixed impacts depending on the penetration rate.

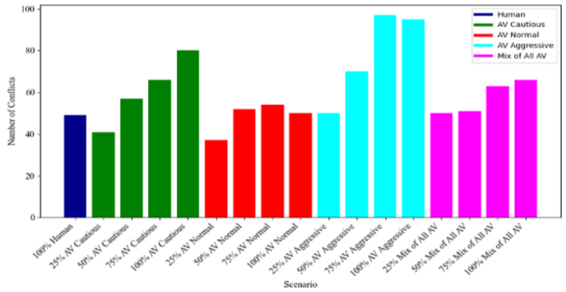


Figure 10 Rear-End Conflicts for Different AV Behaviors and Penetration Rates Before Calibration.

Figure 11 illustrates the influence of AV behavior on lane-change conflicts. With 100% human-driven vehicles, the number of lane-change conflicts recorded was 27. When cautious AVs were introduced at penetration rates of 25%, 50%, 75%, and 100%, the lane-change conflicts increased to 34, 32, 52, and 42, respectively. Normal AV behavior resulted in 23, 22, 26, and 35 lane-change conflicts at the same penetration rates. Conversely, aggressive AV behavior showed counts of 24, 21, 14, and 29 lane-change conflicts. These results indicate that normal AV behavior tends to reduce lane-change conflicts, while cautious and aggressive behaviors can lead to higher lane-change conflicts at certain penetration rates.

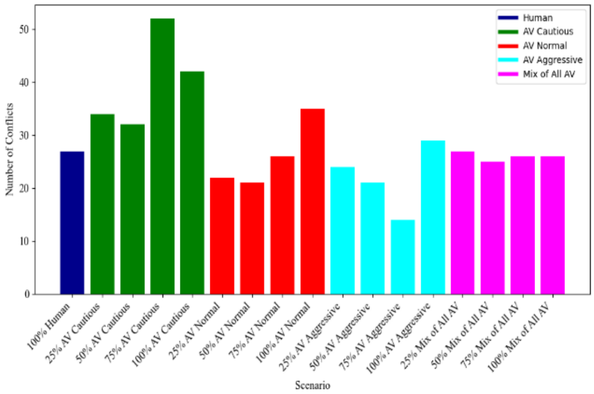


Figure 11 Lane-Change Conflicts for Different AV Behaviors and Penetration Rates Before Calibration.

Figure 12 presents the total number of conflicts across all types, highlighting the significant impact of AV behaviors and penetration rates. In the scenario with 100% human-driven vehicles, a total of 107 conflicts were recorded. The introduction of cautious AVs resulted in total conflicts of 102, 96, 130, and 123 at penetration rates of 25%, 50%, 75%, and 100%, respectively. In contrast, normal AV behavior recorded 74, 92, 88, and 86 total conflicts across the same penetration rates.

Aggressive AV behavior led to totals of 95, 101, 118, and 125 conflicts. Notably, the mixed AV behavior scenario demonstrated a moderate reduction in total conflicts, with counts of 93, 83, 96, and 96 as the penetration rates increased.

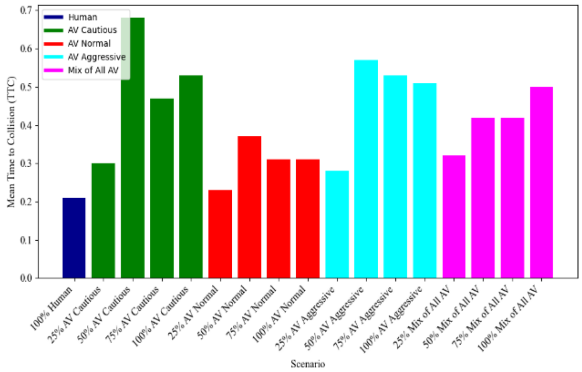


Figure 12 Total Conflicts for Different AV Behaviors and Penetration Rates Before Calibration.

Figure 13 illustrates the Mean Time to Collision (TTC) values, which provide insights into the severity of potential conflicts at the intersection. In the human-driven vehicle scenario, Mean TTC was recorded at 0.21 seconds. For cautious AVs, the Mean TTC values were 0.3, 0.68, 0.47, and 0.54 seconds at penetration rates of 25%, 50%, 75%, and 100%, respectively. Normal AV behavior exhibited Mean TTC values of 0.24, 0.37, 0.31, and 0.31 seconds, while aggressive AV behavior recorded values of 0.27, 0.57, 0.54, and 0.51 seconds. These findings suggest that cautious AVs lead to an increase in Mean TTC, indicating less severe but more frequent conflicts, while normal and aggressive AV behaviors maintain a relatively consistent Mean TTC.

4.2. Impact of AV on conflicts point after calibration

Figure 14 presents the results after calibration, showing a significant reduction in conflict points. In the scenario with human-driven vehicles, there were 14 crossing conflicts. Cautious AVs exhibited 18, 4, 0, and 0 conflicts at penetration rates of 25%, 50%, 75%, and 100%, respectively. Normal AVs recorded 16, 7, 3, and 0 conflicts, while aggressive AVs showed 11, 3, 2, and 0 conflicts. These results indicate a marked improvement in traffic safety following the calibration adjustments.

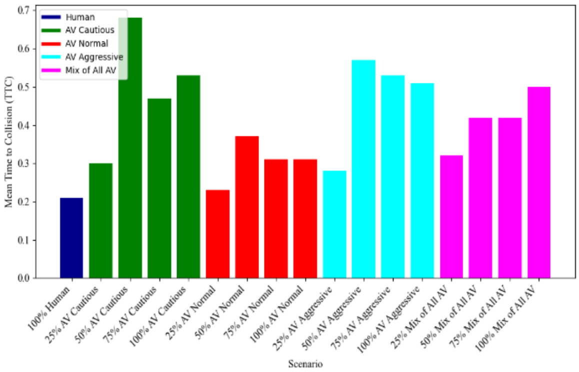


Figure 13 Mean Time to Collision (TTC) for Different AV Behaviors and Penetration Rates Before Calibration.

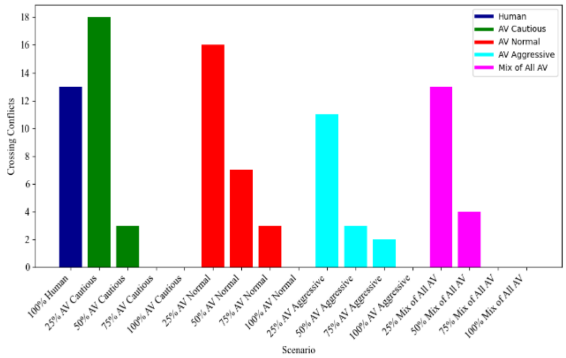


Figure 14 Crossing Conflicts for Different AV Behaviors and Penetration Rates After Calibration.

Figure 15 illustrates the results for rear-end conflicts following the calibration. In the scenario with human-driven vehicles, there were 15 rear-end conflicts recorded. Cautious AVs exhibited 9, 8, 7, and 5 conflicts at increasing penetration rates. Normal AVs showed 8, 8, 11, and 7 conflicts, while aggressive AVs recorded 9, 11, 14, and 12 conflicts. These findings highlight the varying impact of different AV behaviors on rear-end conflict occurrences.

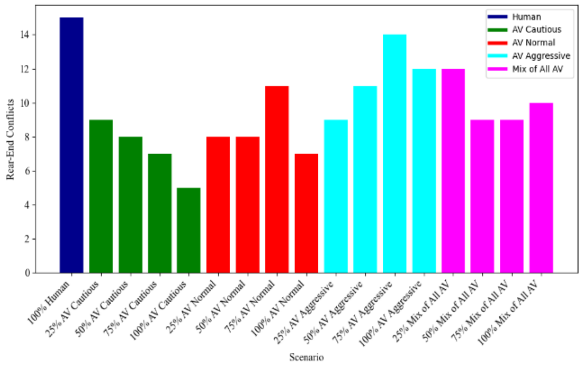


Figure 15 Rear-End Conflicts for Different AV Behaviors and Penetration Rates After Calibration.

Figure 16 shows the results for lane-change conflicts following the calibration. Lane-change conflicts were minimal post-calibration, with human-driven vehicles recording 0 conflicts. Cautious AVs exhibited 1, 1, 1, and 3 conflicts at increasing penetration rates. Normal AVs had 0, 4, 2, and 2 conflicts, while aggressive AVs recorded 1, 2, 4, and 7 conflicts.

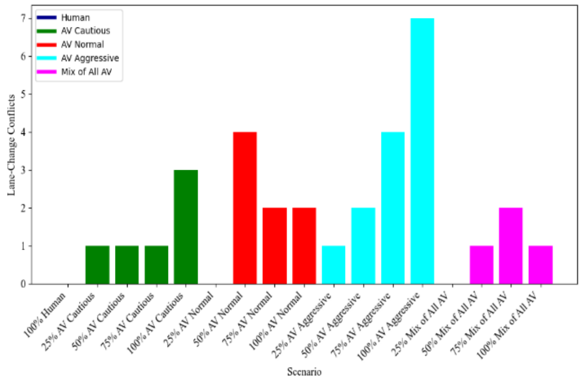


Figure 16 Lane-Change Conflicts for Different AV Behaviors and Penetration Rates After Calibration.

Figure 17 illustrates the total conflicts observed during the study. Human-driven vehicles recorded 29 total conflicts. Cautious AVs showed a decrease in conflicts, with totals of 28, 13, 8, and 8 at increasing penetration rates. Normal AVs had 24, 19, 16, and 10 conflicts, while aggressive AVs recorded 21, 16, 19, and 20 conflicts. These findings suggest that cautious AV behavior is associated with a significant reduction in total conflicts, particularly at higher penetration rates.

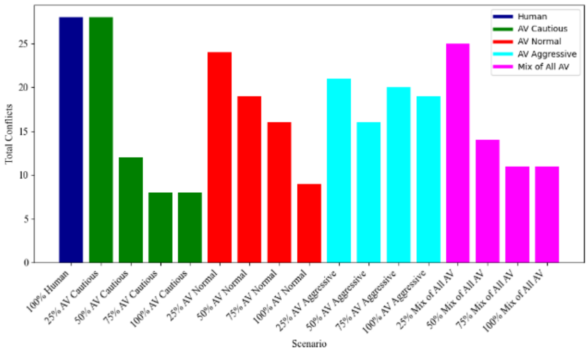


Figure 17 Total Conflicts for Different AV Behaviors and Penetration Rates After Calibration.

Figure 18 illustrates the Mean Time to Collision (TTC) observed in the study. Mean TTC increased post-calibration, indicating less severe conflicts. Human-driven vehicles had a Mean TTC of 0.48 seconds. Cautious AVs recorded Mean TTC values of 0.3, 0.42, 0.55, and 0.35 seconds. Normal AVs exhibited Mean TTC values of 0.32, 0.23, 0.57, and 0.43 seconds, while aggressive AVs showed values of 0.37, 0.58, 0.79, and 0.72 seconds. These results suggest that the post-calibration adjustments contributed to a reduction in conflict severity across all vehicle types.

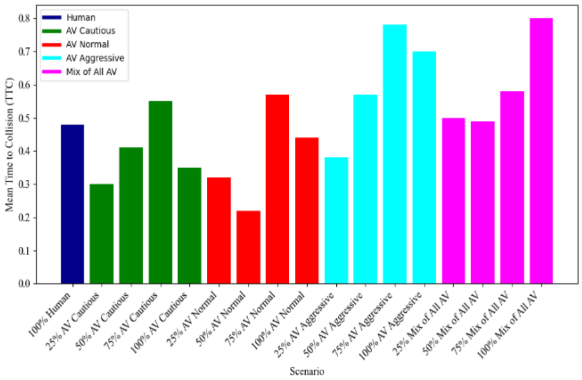


Figure 18 Mean Time to Collision (TTC) for Different AV Behaviors and Penetration Rates After Calibration.

5. Conclusion

After calibration, normal AV behavior balanced safety and efficiency, cautious AVs increased Mean Time to Collision (TTC), aggressive AVs reduced crossing conflicts but increased rear-end conflicts, and mixed AV improved overall safety. These findings underscore the need for tailored intersection designs to optimize AV integration and enhance traffic safety and efficiency.

These findings underscore the importance of designing intersection controls tailored to specific AV behaviors, with the aim of optimizing both traffic safety and efficiency. Future research should focus on real-world AV deployments to validate these simulation-based insights. Additionally, investigating the impact of varying AV penetration rates, vehicle-to-infrastructure (V2I) communication, and human-AV interaction in more complex traffic scenarios will be crucial for advancing the safe integration of AVs into urban networks. The development of dynamic signal control systems that can adapt to different AV driving behaviors and changing traffic conditions will also be essential for enhancing overall traffic management.

CRediT authorship contribution statement

Mustafa Albdairi: Conceptualization, Methodology, Software, Writing - Original Draft. Ali Almusawi: Supervision, Validation, Resources, Writing - Review & Editing. Syed Shah Sultan Mohiuddin Qadri: Data Curation, Investigation, Formal Analysis, Review &

Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgement

The authors would like to thank Çankaya University for providing the necessary resources and tools to carry out this research. Special thanks to the Department of Civil Engineering and the Department of Industrial Engineering for their support and guidance throughout the study.

6. References

1. A. Karbasi and S. O’Hern, “Investigating the impact of connected and automated vehicles on signalized and unsignalized intersections safety in mixed traffic,” Future Transportation, vol. 2, no. 1, pp. 24-40, 2022.
2. Albdairi, Mustafa, Ali Almusawi, and Syed Shah Sultan Mohiuddin Qadri, “Impact of Autonomous Vehicle Driving Behaviors on Signalized Intersection Performance: A Review,” Usak University Journal of Engineering Sciences, vol. 7, no. 1, pp. 14-26, June 2024.
3. W. Do, N. Saunier, and L. Miranda-Moreno, “Safety benefits of automated speed advisory systems at signalized intersections,” Transportation Research Record, vol. 2677, no. 3, pp. 551-564, 2023.
4. A. I. Mahbub, V.-A. Le, and A. A. Malikopoulos, “Safety-Aware and Data-Driven Predictive Control for Connected Automated Vehicles at a Mixed Traffic Signalized Intersection,” IFAC-Papers online, vol. 55, no. 24, pp. 51-56, 2022.
5. G. Bathla et al., “Autonomous vehicles and intelligent automation: Applications, challenges, and opportunities,” Mobile Information Systems, vol. 2022, no. 1, p. 7632892, 2022.
6. M. Khayatian et al., “A survey on intersection management of connected autonomous vehicles,” ACM Transactions on Cyber-Physical Systems, vol. 4, no. 4, pp. 1-27, 2020.
7. E. Namazi, J. Li, and C. Lu, “Intelligent intersection management systems considering autonomous vehicles: A systematic literature review,” IEEE Access, vol. 7, pp. 91946-91965, 2019.
8. E. F. Ozioko, J. Kunkel, and F. Stahl, “Road intersection coordination scheme for mixed traffic (human-driven and driverless vehicles): A systematic review,” in Science and Information Conference, Springer, pp. 67-94, 2022.
9. S. K. Jayaraman et al., “Pedestrian trust in automated vehicles: Role of traffic signal and AV driving behavior,” Frontiers in Robotics and AI, vol. 6, p. 117, 2019.
10. I. R. Khan, Interaction Between Autonomous Vehicles and Other Road Users—A Simulation Study. The University of Alabama in Huntsville, 2023.
11. M. Martínez-Díaz, F. Soriguera, and I. Pérez, “Autonomous driving: a bird's eye view,” IET Intelligent Transport Systems, vol. 13, no. 4, pp. 563-579, 2019.
12. J. Wang, Y. V. Pant, L. Zhao, M. Antkiewicz, and K. Czarnecki, “Enhancing safety in mixed traffic: Learning-based modeling and efficient control of autonomous and human-driven vehicles,” IEEE Transactions on Intelligent Transportation Systems, 2024.
13. H. Sadid and C. Antoniou, "A simulation-based impact assessment of autonomous vehicles in urban networks," IET Intelligent Transport Systems, 2024. doi: 10.1049/itr2.12537.
14. S. Kim, M.-J. Cho, and Y. Lee, “Exploration of traffic accident-based pilot zones for autonomous vehicle safety validation,” Electronics, 2024. doi: 10.3390/electronics13173390.
15. Federal Highway Administration, “Surrogate Safety Assessment Model (SSAM) User Manual,” U.S. Department of Transportation, Publication No. FHWA-HRT-08-050, 2008. Available at: https://highways.dot.gov/sites/fhwa.dot.gov/files/FHWA-HRT-08-050.pdf.

16. A. Osman, “Evaluation of the Impact of Automated Driven Vehicles on Traffic Performance at Four-leg Signalized Intersections,” Linköping University, Department of Science and Technology, Communications and Transport Systems, Linköping University, Faculty of Science & Engineering, 2023.

17. Almusawi, A., & Albdairi, M. “The Impact of Increasing Traffic Volume on Autonomous Vehicles in Roundabout,” Akıllı Ulaşım Sistemleri Ve Uygulamaları Dergisi, 2024.

18. A. Almusawi, M. Albdairi, and S.S.S.M. Qadri, "Integrating Autonomous Vehicles (AVs) into Urban Traffic: Simulating Driving and Signal Control," Applied Sciences, vol. 14, no. 19, pp. 8851, Oct. 2024. doi: https://doi.org/10.3390/app14198851.