e-ISSN: 2564-7954 CUSJE 22(1): 001-015 (2025) Research Article

Çankaya University

Journal of Science and Engineering

CUJSE

https://dergipark.org.tr/cankujse

Impact of Increased Heavy Vehicle Traffic on Three-Leg Intersections: A Case Study on Traffic Flow and Congestion Analysis

Mustafa Albdairi[1], Zeynep Demirel[1], Öykü Pehlivan[1], Ece Esirgün[1], Ali Almusawi[1*]

[1] Deparment of Civil Engineering, Çankaya University, Ankara/Türkiye

Keywords

Heavy vehicles,
Traffic congestion,
Traffic flow,
Urban mobility,
Queue length.

Abstract

The increasing presence of heavy vehicles in urban road networks significantly affects traffic flow, congestion levels, and intersection performance. This study examines the impact of heavy vehicle growth on a 3-leg T-intersection located in Atayurt, Ankara. Traffic data were collected through video observation, and three scenarios were analyzed: the initial case with real-world traffic conditions, a 50% increase in heavy vehicle volume, and a 100% increase. The findings reveal that as heavy vehicle density rises, congestion worsens, particularly in critical sections (C2 and C3), leading to increased delays and reduced speeds. The study also highlights the importance of optimized signal timing and traffic management strategies in mitigating congestion. Recommendations such as dedicated lanes for heavy vehicles, intersection capacity expansion, and dynamic signal adjustments are proposed to enhance intersection efficiency. The insights from this study contribute to a better understanding of traffic dynamics in mixed-vehicle environments and inform urban traffic planning efforts.

1. Introduction

1.1. Background

Urban road networks are essential to successful mobility, but they face increasing challenges with increasing traffic volumes, particularly from heavy vehicles. Trucks, buses, and freight carriers contribute to industrial and business activities, but their operation has a tremendous impact on general traffic performance. Unlike passenger cars, heavy vehicles consume more space, accelerate more slowly, and have longer braking distances [1-3]. These lead to congestion, longer queue lengths, and longer travel times, particularly in high-density urban areas with intersections as critical points of bottleneck [4, 5]. Of these, 3-leg T-intersections are critical locations in urban networks with multiple streams of traffic crossing. Signal timing, vehicle mix, and general traffic flow govern their efficiency. A high proportion of heavy vehicles at these intersections can disrupt traffic by taking longer to clear, occupying more road space, and interrupting the even flow of vehicles. Furthermore, they complicate maneuvering due to weight and dimensions, causing delays and congestion in high-traffic areas [6-8].

Increased industrialization and urbanization in recent times have led to a high rate of heavy vehicle traffic in city roads, particularly around industries [9]. This has been seen in urban areas like Ankara, Turkey, with industrial hubs contributing a high rate of freight traffic. The Atayurt, Ankara, 3-leg T-intersection is such a location with a high rate of heavy vehicle traffic due to proximity to an industrial hub. It serves as a critical link between highways and local roads and plays a central role in goods and services transportation. The high rate of heavy vehicles in the area has, however, caused delays in travel time, traffic congestion, and potential safety risks. The

* Corresponding Author: ali.almusawi@cankaya.edu.tr
Received: March 9, 2025, Accepted: March 26, 2025

mixed traffic nature, with heavy vehicles and cars, makes these problems complex. Cars have shorter break and acceleration times than heavy vehicles and can thus pass through intersections more efficiently. This flow, however, gets interrupted by heavy vehicles, and break and stop delays increase. These problems necessitate effective traffic management to offset the negative impacts of heavy vehicle congestion [10].

Given rising concerns about traffic efficiency in urban environments, it is critical to examine heavy vehicle presence at intersections and develop evidence-based strategies for improvement. This study will examine traffic performance with varying penetration levels of heavy vehicles and provide appropriate recommendations for improving intersection operation [11, 12].

1.2. Research Problem

Increased heavy vehicle proportion in mixed traffic leads to significant problems for intersection performance and traffic efficiency in general. Some key problems that arise due to heavy vehicles include:

1. Consume more space and have worse maneuverability, and they create jams at strategic locations.
2. Reduced Speeds and Increased Delays: The acceleration and braking performance by heavy vehicles contribute to speed variation and longer stop times.
3. Queue Formation at Intersections: The high clearance time of heavy vehicles increases queue lengths and affects intersection capacity.
4. Safety Concerns: The interaction between heavy vehicles and passenger cars at intersections increases the likelihood of traffic conflicts and accidents.

Given these challenges, there is a clear necessity to study the specific impact of heavy vehicle presence in urban intersections and provide effective traffic management measures to minimize delay and congestion.

1.3. Objective of The Study

The major aim of this research is to examine the effect of heavy vehicle traffic increase on a 3-leg T-intersection's operational efficiency. Precisely, the research seeks to:

- Assess Traffic Performance: Evaluate the effect of varying heavy vehicle proportions on traffic flow, speeds, and delays.
- Analyze Congestion Patterns: Identify critical congestion points and examine queue length variations across different scenarios.
- Compare Different Traffic Scenarios: Investigate how an increase of 50% and 100% in heavy vehicle volume affects intersection performance compared to real-world conditions.
- Provide Recommendations: Suggest effective traffic management solutions, such as signal optimization, dedicated heavy vehicle lanes, and alternative routing strategies, to improve intersection efficiency.

With these objectives, this study provides valuable information to traffic engineers and urban planners to enhance intersection performance and accommodate rising mixed-vehicle traffic demand in industrial zones.

2. Literature Review

Traffic inefficiencies and intersection congestion have been widely studied, with emphasis being put particularly on heavy vehicle impacts on traffic performance. Multiple studies have examined how different combinations of vehicles affect traffic flow, queue length, and delay time, with emphasis being put on heavy vehicles' central role in intersection dynamics. It has been observed that heavy vehicles have longer breaking, and acceleration times compared to passenger cars, with longer stop delay and a reduction in intersection capacity. Additionally, a proportionally increased concentration of heavy vehicles in signalized intersections has been linked to queue formation, traffic density, and a reduction in average speeds in mixed-traffic flow [13-15].

Numerous studies have utilized microscopic traffic simulation software, field observations, and statistical modeling to study heavy vehicle impacts on intersection performance. The studies have revealed how percentages of heavy vehicles differ and thereby influence levels of congestion and intersection capacity. Results from these studies provide a basis for interpreting traffic performance at bottleneck junctions and planning effective traffic management. Table 1 gives a review of some studies in terms of heavy vehicle impacts on intersection performance, outlining objectives, methodology, and results [16, 26].

Table 1. Overview of Studies Investigating Heavy Vehicle Effects on Traffic Performance

Reference	Year	Study Objective	Methodology/Tools Used	Key Findings
[16]	2018	Analyzed traffic flow at a busy 3-leg intersection in Vellore, India.	Video-based traffic surveys and volume analysis.	Heavy motorized vehicles (HMVs) accounted for 7% of total traffic, increasing congestion. Future traffic growth may necessitate infrastructure improvements like a flyover or grade separator.
[17]	2018	Evaluated the impact of overloaded heavy vehicles on freeway conditions.	Multi-class traffic flow model based on Smulders' fundamental diagram.	Overloaded heavy vehicles increased congestion and extended traffic delays. The model accurately captured traffic conditions.
[18]	2019	Identified risks associated with traffic congestion caused by heavy vehicles.	Fault Tree Analysis (FTA), Social Network Analysis (SNA), and Probability & Impact Matrix techniques.	Heavy vehicle congestion results from infrastructure issues and policy gaps. A risk management framework can mitigate traffic disruptions.
[19]	2019	Examined mixed-traffic congestion levels in developing nations.	Passenger Car Equivalent (PCE) calculations and maximum capacity analysis.	High proportions of small vehicles (e.g., motorcycles) contribute to marginal road congestion, requiring improved traffic management.
[20]	2021	Evaluated unconventional intersection designs under heavy traffic conditions.	VISSIM traffic simulation and CRITIC decision-making method.	Unconventional intersection designs (PFI, CFI) outperform conventional setups under high traffic loads, improving intersection efficiency.
[21]	2021	Investigated whether heavy vehicles always negatively affect traffic flow.	Data collection from piezoelectric sensors on a highway.	Heavy vehicles reduce average speed but also decrease vehicle-to-vehicle conflict, sometimes stabilizing traffic.
[22]	2022	Assessed how overloaded heavy vehicles impact freeway service levels.	Microsimulation modeling and primary data collection.	Overloaded heavy vehicles degrade the level of service and cause temporary speed fluctuations.
[23]	2022	Studied the impact of heavy vehicle platoons on mixed-traffic highway conditions.	Infrared sensors for time headway measurement and mean relative speed analysis.	Heavy vehicle platooning reduces traffic efficiency by increasing travel time and congestion.
[24]	2024	Compared aggressive HGV platoons to human-driven HGVs at signalized intersections.	PTV VISSIM microscopic simulation with 12 traffic scenarios.	Aggressive HGV platoons improve traffic flow, reduce delays, and lower emissions compared to human-driven HGVs.
[25]	2024	Assessed traffic performance differences between human-driven and automated HGVs in urban and highway networks.	PTV VISSIM simulation of queue lengths, delays, and emissions.	Automated HGVs reduce congestion and queue lengths but require optimized signal settings for the best results.
[26]	2024	Analyzed the effects of heavy vehicle lane changes on urban traffic flow.	VISSIM traffic simulation of lane change scenarios.	Increased heavy vehicle lane changes reduce average speeds, but designated lanes can improve traffic performance.

Recent studies have continued to emphasize the substantial impact of heavy vehicles on intersection performance and overall urban traffic flow. For instance, Pan et al. [4] highlighted how congestion parameters and dynamic

discharge processes are significantly influenced by heavy vehicle concentrations in urban bottleneck. Similarly, Albdairi et al. [24] found that aggressive heavy goods vehicle (HGV) platoons at signalized intersections can improve traffic flow and reduce delays compared to human-driven HGVs. Almusawi et al, [25] demonstrated that automated HGVs contribute to reduced congestion and queue lengths but require proper signal optimization to maximize benefits [25]. Sari and Mauramdha further analyzed how frequent lane changes by heavy vehicles reduce average traffic speeds, suggesting that dedicated lanes could enhance performance [26]. Bonela and Kadali explored vehicle-type impacts on conflicts at unsignalized intersections, revealing that heavy vehicles increase crossing conflicts, particularly during right-turn maneuvers [6]. Additionally, unconventional intersection designs have shown promise in alleviating congestion under high traffic loads, as discussed by Pan et al. [20]. Collectively, these studies underline the necessity of integrating dynamic traffic management strategies—such as adaptive signal control, designated lanes for heavy vehicles, and geometric improvements to mitigate congestion and enhance intersection efficiency in mixed-traffic environments.
These studies have extensively examined heavy vehicle impacts on traffic flow, congestion, and intersection performance. Microscopic traffic simulations, field observations, and mathematical modeling have been applied to examine traffic in various situations. Previous studies have examined heavy vehicle ratios' impacts on levels of congestion, queue length, travel speed, and intersection capacity. Some have looked at freeway environments and freeway segments, while others have looked at alternative intersection geometries and whether they can improve traffic efficiency. While these studies provide a lot of insight into traffic dynamics, there remains a call for more studies into varying intensities of heavy vehicle presence and how these varying intensities impact intersection performance, particularly in mixed-traffic environments. More detailed assessments are required to ascertain to what degree increasing heavy vehicle volumes impact key traffic measures, such as queue formation, stop delay, and travel speed reductions, in various urban traffic environments.

This study addresses part of this gap by investigating the impact of increased heavy vehicle presence at a 3-leg T-intersection in real traffic. Unlike previous studies focusing primarily on general traffic performance or freeway congestion, this study investigates how different heavy vehicle penetration levels impact intersection efficiency and trends in congestion. Through video-based traffic field observations and microscopic simulation, this study offers a detailed assessment of queue length, stop delay, and speed fluctuation as heavy vehicle ratios vary. This study also offers practical traffic management strategy recommendations, such as signal timing and heavy vehicle lane options, to improve intersection efficiency. The findings will inform urban planners and decision makers to develop more effective measures to alleviate congestion and improve traffic flow in industrial and high-volume freight corridors.

3. Methodology

3.1. Methodology Overview

This study employs a data-driven approach to examine the impact of high numbers of heavy vehicles in a 3-leg T-intersection in a city setting. The approach involves traffic data collection, generation of scenarios, and performance assessment. A video-based traffic monitoring method was used to record real traffic movements in the intersection. Subsequent analysis was performed to separate passenger cars and heavy vehicles to support a detailed assessment of traffic mix. Additionally, vehicle speed and travel time observations were collected from recorded videos to investigate congestion levels and delay patterns.

To understand the effects of heavy vehicle penetration, three traffic scenarios were designed:

a) Initial Case: Real-world traffic conditions with the existing percentage of heavy vehicles.
b) 50% Increase in Heavy Vehicles: Simulated scenario with a moderate increase in heavy vehicle volume.
c) 100% Increase in Heavy Vehicles: Scenario modeling a significant rise in heavy vehicle presence.

Each scenario was assessed in terms of queue length, speed variations, and stop delays to determine the extent to which heavy vehicles contribute to congestion at the intersection. The flowchart in Figure 1 illustrates the overall methodology, from data collection to analysis and result interpretation.

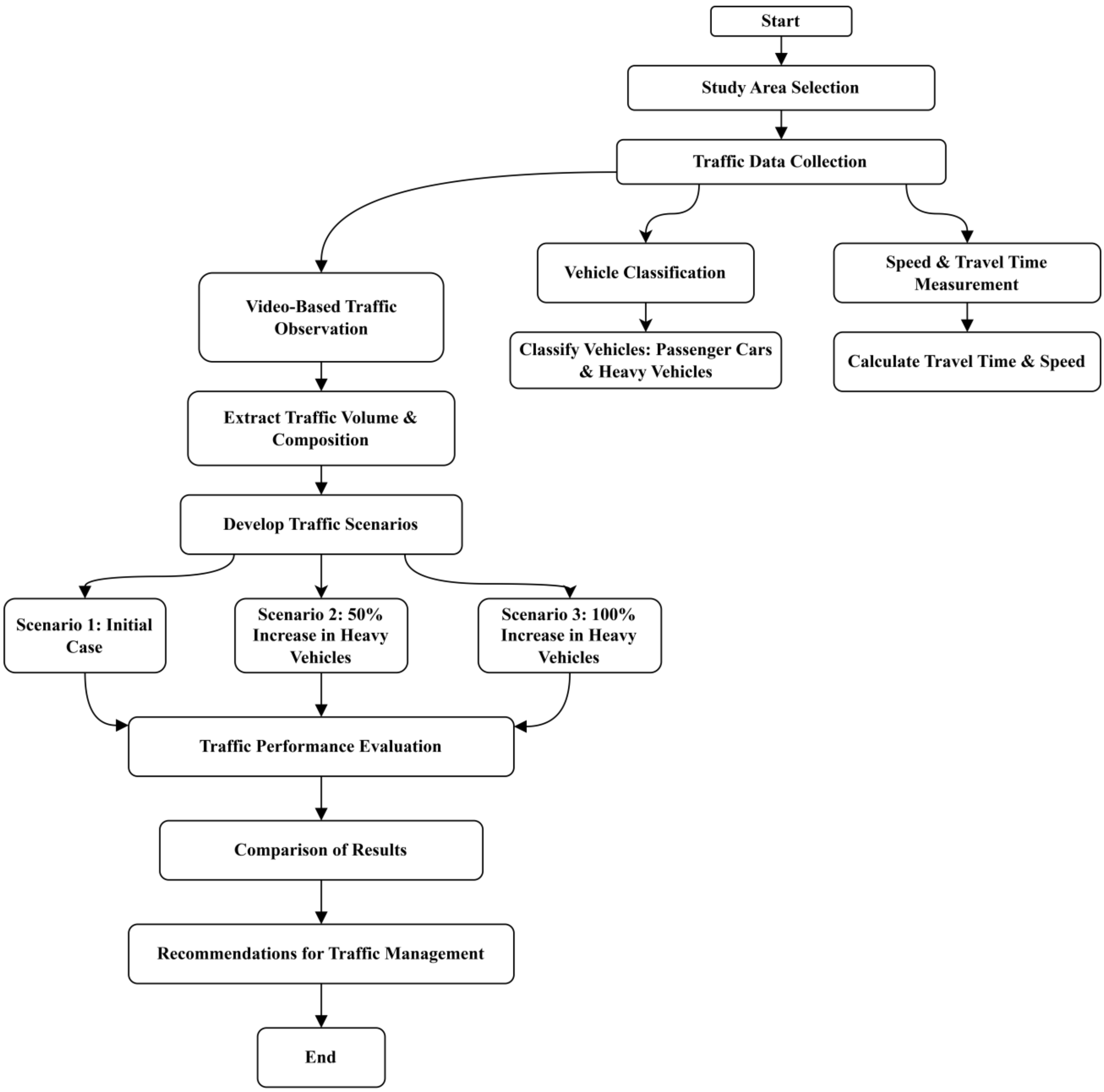
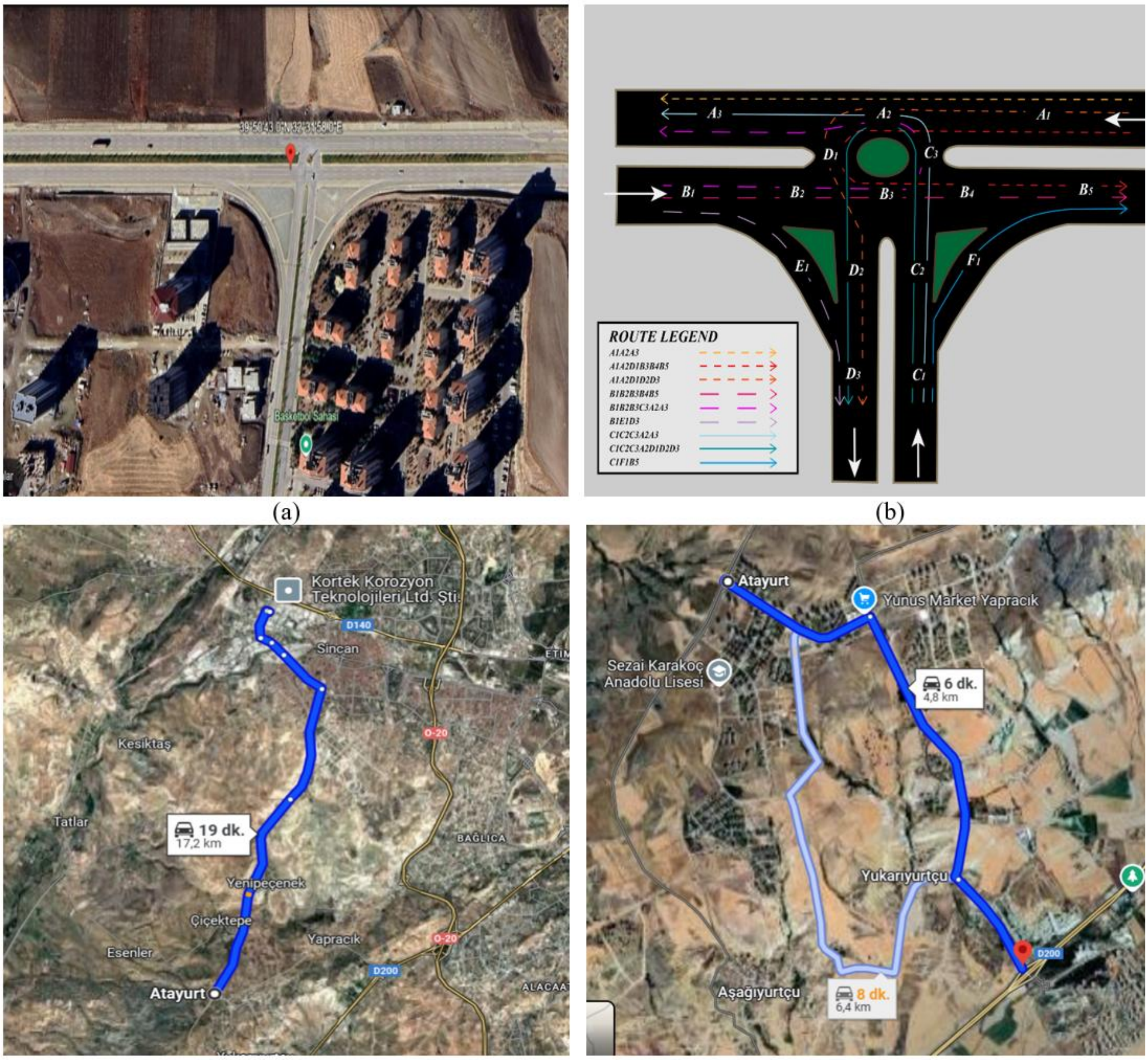


Figure 1. Overview of Research Methodology

3.2. Study Area and Intersection Description

The study was conducted at a 3-leg T-intersection located in Atayurt, Ankara, Turkey, which experiences significant traffic congestion due to its proximity to industrial zones. The intersection serves as a critical connection between local roads and major highways, facilitating the movement of both passenger vehicles and heavy vehicles, including trucks and freight carriers. Due to the high proportion of heavy vehicles using the intersection, delays and congestion frequently occur, affecting overall traffic performance (Figure 2(a)).

The intersection layout consists of three approach legs, where vehicles perform left turns, right turns, and through movements. The road network configuration and vehicle paths at the intersection are illustrated in Figure 2(b). The right leg of the intersection connects to the Sincan Organized Industrial Zone, a major industrial hub, contributing to the high volume of heavy vehicle traffic (Figure 2(c)). Meanwhile, the left leg leads to Dumlupınar Boulevard (E90 Highway), a major arterial road that links the area to regional and national transportation networks (Figure 2(d)). Absence of advanced traffic management systems such as dynamic signal timing or real-time monitoring worsens congestion in peak hours. All these factors make this location an ideal location for analyzing the impacts of heavy vehicle penetration on intersection performance.



(c) (d)

Figure 2. Study Area, Intersection Layout, and Key Routes (a) Aerial View of the 3-Leg T-Intersection, (b) Intersection Layout and Vehicle Paths, (c) Route to Sincan Organized Industrial Zone, (d) Route to Dumlupınar Boulevard (E90 Highway)

3.3. Why Was This Intersection Selected?

Local survey results make this a high-risk area (Figure 3) with a history of frequent accidents. Lack of speed control systems and real-time monitoring increases the speed differences between passenger vehicles and heavy vehicles, thereby enhancing the risk of collisions and traffic disturbance. The observed crash data indicates a need for further analysis and potential safety improvements at this intersection.

Figure 3. Key Factor for Selecting the Study Intersection

3.4. Data Collection Methods

A data collection approach was adopted to assess the impacts of heavy vehicles on intersection performance. The study applied video-based traffic observation followed by vehicle classification and speed measurement analysis. This data provided critical information on traffic flow characteristics, vehicle composition, and congestion patterns at the study intersection.

A stationary camera was set up near the intersection to capture continuous traffic movements. The camera was positioned at an elevated angle to capture all approach legs. Traffic flow patterns, congestion hotspots and vehicle composition were extracted manually from the recorded footage. The video observations allowed accurate tracking of vehicle types, movement paths and signal compliance to inform subsequent analyses.

The video footage showed vehicles categorized as passenger vehicles and heavy vehicles. Passenger vehicles included cars and motorcycles while heavy vehicles included trucks, buses and freight carriers. The classification assessed how different vehicle types create congestion and travel delays at the intersection. Table 2 lists the categorized vehicle types and their movements.

Table 2. Vehicle Classification Based on Movement Direction

Route ID	Edges	Vehicle Type
1	A1-A2-A3	Passenger Vehicle
2	A1-A2-A3	Heavy Vehicle
3	A1-A2-D1-B3-B4-B5	Passenger Vehicle
4	A1-A2-D1-B3-B4-B5	Heavy Vehicle
5	A1-A2-D1-D2-D3	Passenger Vehicle
6	A1-A2-D1-D2-D3	Heavy Vehicle
7	B1-B2-B3-B4-B5	Passenger Vehicle
8	B1-B2-B3-B4-B5	Heavy Vehicle
9	B2-B3-C3-A2-A3	Heavy Vehicle
10	B2-B3-C3-A2-A3	Passenger Vehicle
11	B1-E1-D3	Passenger Vehicle
12	B1-E1-D3	Heavy Vehicle
13	C1-C2-C3-A2-A3	Passenger Vehicle
14	C1-C2-C3-A2-A3	Heavy Vehicle
15	C1-C2-C3-A2-D1-D2-D3	Passenger Vehicle
16	C1-C2-C3-A2-D1-D2-D3	Heavy Vehicle
17	C1-F1-B5	Passenger Vehicle
18	C1-F1-B5	Heavy Vehicle

To further analyze the effect of heavy vehicle presence on traffic flow, vehicle speed and travel time were assessed by the distance-time approach. Vehicles were followed between two reference points, and their speeds were calculated from formula 1&2:

$$Speed\ (m/s) = \frac{Distance\ (meters)}{Time\ (seconds)} \tag{1}$$

$$Speed\ (km/h) = Speed\ (m/s)\ \times 3.6 \tag{2}$$

The results of these calculations, categorized by vehicle type and movement direction, are presented in Table 3.

Table 3. Speed Data for Different Vehicle Types in the Study Area

Vehicle Type	Speed (m/s)	Speed (km/h)
A Direction Heavy Vehicle	16	57.6
A Direction Passenger Vehicle	23	82.8
B Direction Heavy Vehicle	12	43.8
B Direction Passenger Vehicle	17	61.2
Turning Heavy Vehicle	6	21.6
Turning Passenger Vehicle	10	36
Right-Left Heavy Vehicle	12	43.2
Right-Left Passenger Vehicle	17	61.2

The data in Table 3 shows that passenger vehicles generally travel at higher average speeds compared to heavy vehicles, with the most significant reductions observed during turning movements. These lower turning speeds for heavy vehicles contribute to increased congestion and longer travel times at the intersection, especially in high-conflict areas.

Combining video-based observations, vehicle classification and speed analysis, the operation impact of heavy vehicles at the intersection is assessed. The gathered data is the basis for scenario evaluation and traffic performance analysis in the following sections.

3.5. Simulation Parameters

The simulation environment was developed in SUMO to accurately replicate the geometry and traffic dynamics of the 3-leg T-intersection under study. Specific vehicle parameters were defined for both passenger vehicles and heavy vehicles to reflect realistic driving characteristics, based on typical urban traffic conditions and field observations. These parameters ensured that vehicle behavior, congestion formation, and interaction between passenger cars and heavy vehicles were simulated with high accuracy. The simulation parameters used are presented in Table 4.

Table 4. Simulation Parameters for Passenger and Heavy Vehicles

Parameter	Passenger Vehicle	Heavy Vehicle
Vehicle Length (m)	5	12
Minimum Gap (m)	2.5	2.5
Maximum Speed (m/s)	15.43 (55.56 km/h)	7.72 (27.78 km/h)
Acceleration (m/s²)	2.6	2
Deceleration (m/s²)	4.5	4.5
Driver Imperfection (sigma)	0.5	0.5
Reaction Time (tau) (s)	1	1

3.6. Traffic Scenarios

Three traffic scenarios were analyzed to evaluate the impacts of heavy vehicle presence on intersection performance. The first case includes 699 vehicles (148 heavy vehicles and 551 passenger vehicles) collected from real-world traffic conditions using video-based data collection. This scenario represents the baseline comparison case and reflects existing traffic flow dynamics at the intersection. In the 2nd scenario, the quantity of heavy vehicles increased 50% from the original case as the number of motor vehicles stayed constant. This yielded 774 vehicles, 223 heavy vehicles, and 551 passenger vehicles, allowing moderately higher freight traffic and its impact on congestion, queue lengths, and travel delays. The third scenario modeled a 100% increase in heavy vehicles compared to the initial case, representing high freight traffic volume condition. The total vehicle count increased to 850 vehicles, consisting of 299 heavy vehicles and 551 passenger vehicles, simulating worst-case congestion levels to examine how excessive heavy vehicle presence impacts traffic efficiency, delay times, and overall intersection performance. The vehicle distribution across these scenarios is illustrated in Figure 4 & 5.

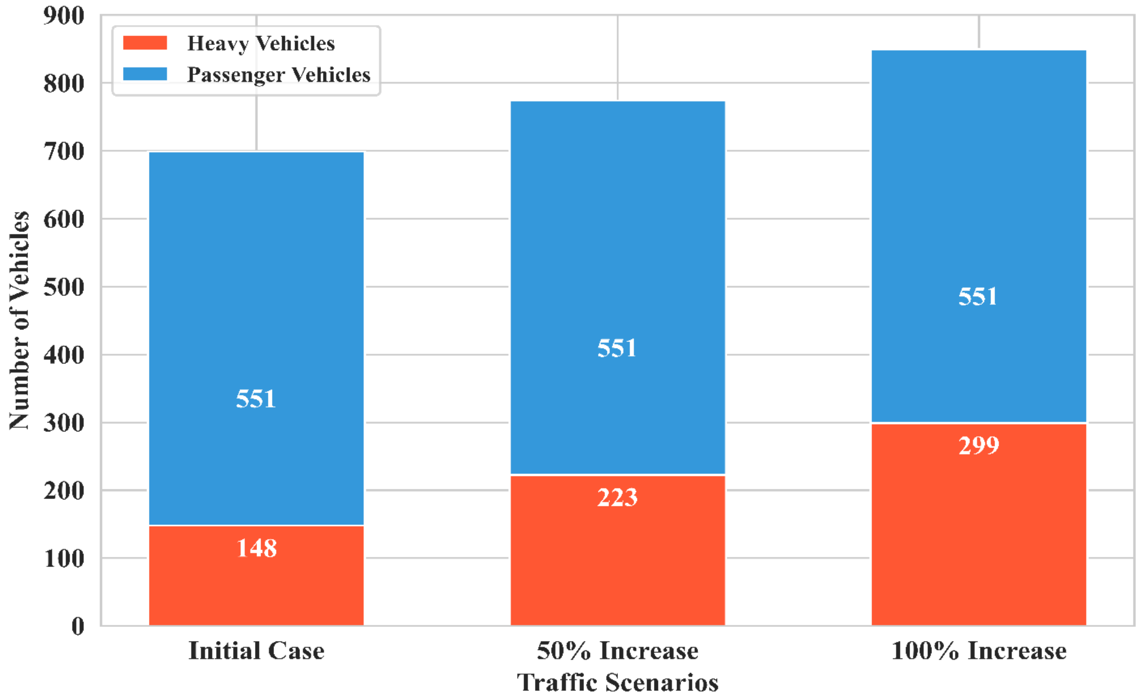


Figure 4. Vehicle Composition Across Traffic Scenarios

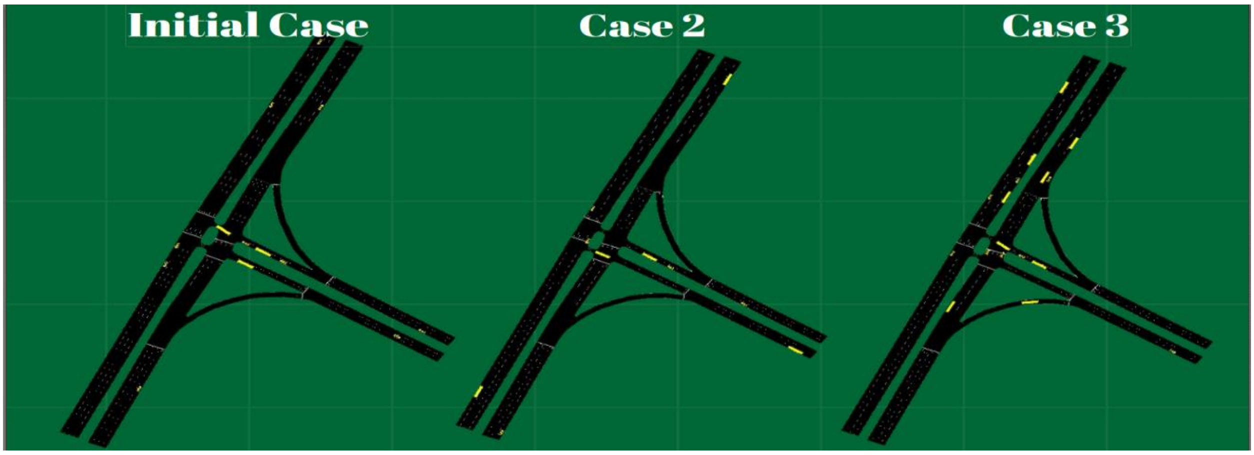


Figure 5. Traffic Scenarios from SUMO Simulation Software

4. Results

4.1. Headway Analysis

Headway, or following time, is a critical indicator of traffic flow efficiency, particularly under varying levels of heavy vehicle penetration. The analysis across different scenarios highlights a clear trend of decreasing headway with increasing heavy vehicle proportions, leading to higher congestion levels and reduced traffic fluidity.

In the initial case (Figure 6), sections E1 and F1 exhibited the highest headway values, indicating relatively smooth traffic flow. Conversely, sections D1 and C3 had significantly lower headway values, suggesting tighter vehicle spacing and congestion hotspots. The mid-range headway values in sections B2, B4, and B5 reflect moderate traffic density, where vehicle interactions were more frequent but not yet at critical congestion levels.

With a 50% increase in heavy vehicles (Figure 7), headway values declined notably in B2, B3, and C2, reflecting increased congestion in these sections. Sections C3 and D3 remained among the most constrained areas, indicating persistent bottlenecks as vehicle spacing tightened. While E1 and F1 continued to maintain higher headway values, they began to show a slight reduction, suggesting a gradual impact of rising heavy vehicle proportions even in less congested sections.

Under 100% increased heavy vehicle conditions (Figure 8), the headway values in critical sections dropped further, exacerbating congestion. The sections that were already experiencing low headway in previous scenarios saw even greater reductions, with C2 and C3 reaching their lowest levels. This confirms that increased heavy vehicle presence intensifies congestion, limits safe following distances, and heightens the risk of traffic flow disruptions.

The results emphasize the necessity of traffic management strategies to address congestion in vulnerable sections, particularly C2, C3, and B2, where heavy vehicle concentration significantly deteriorates traffic conditions. Measures such as optimized signal timing, designated heavy vehicle lanes, and dynamic traffic control systems could help mitigate the worsening headway trends observed in these scenarios.

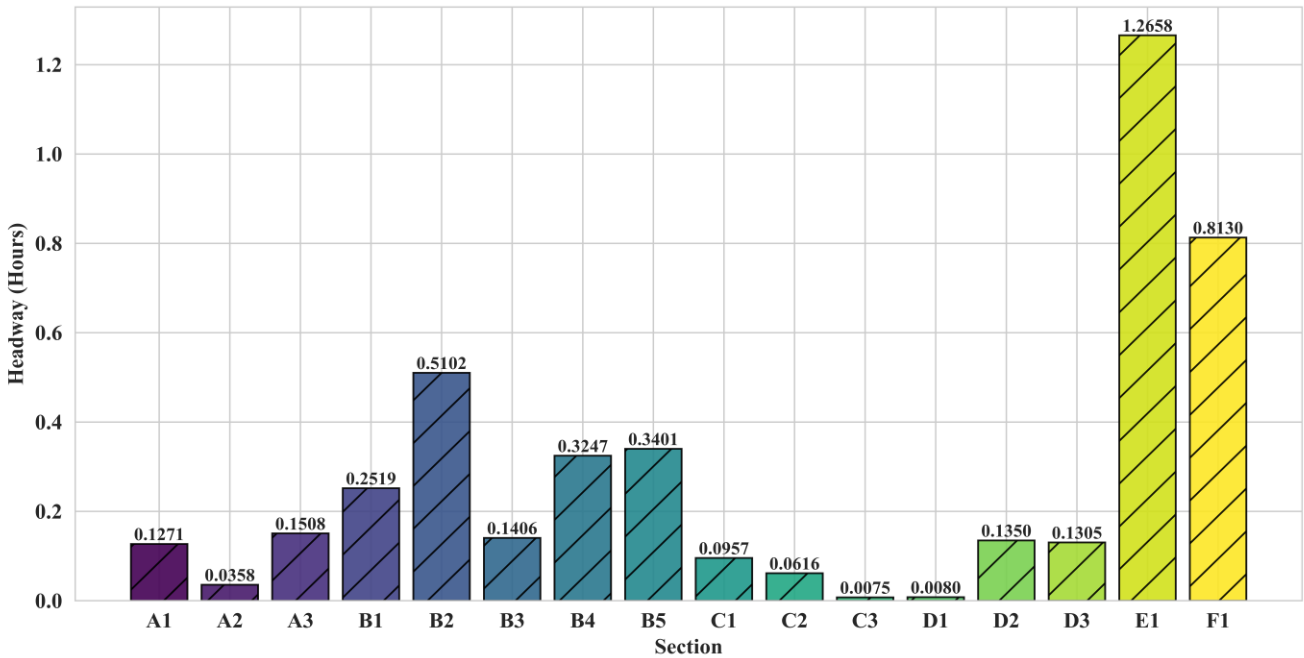


Figure 6. Headway Distribution in the Initial Case

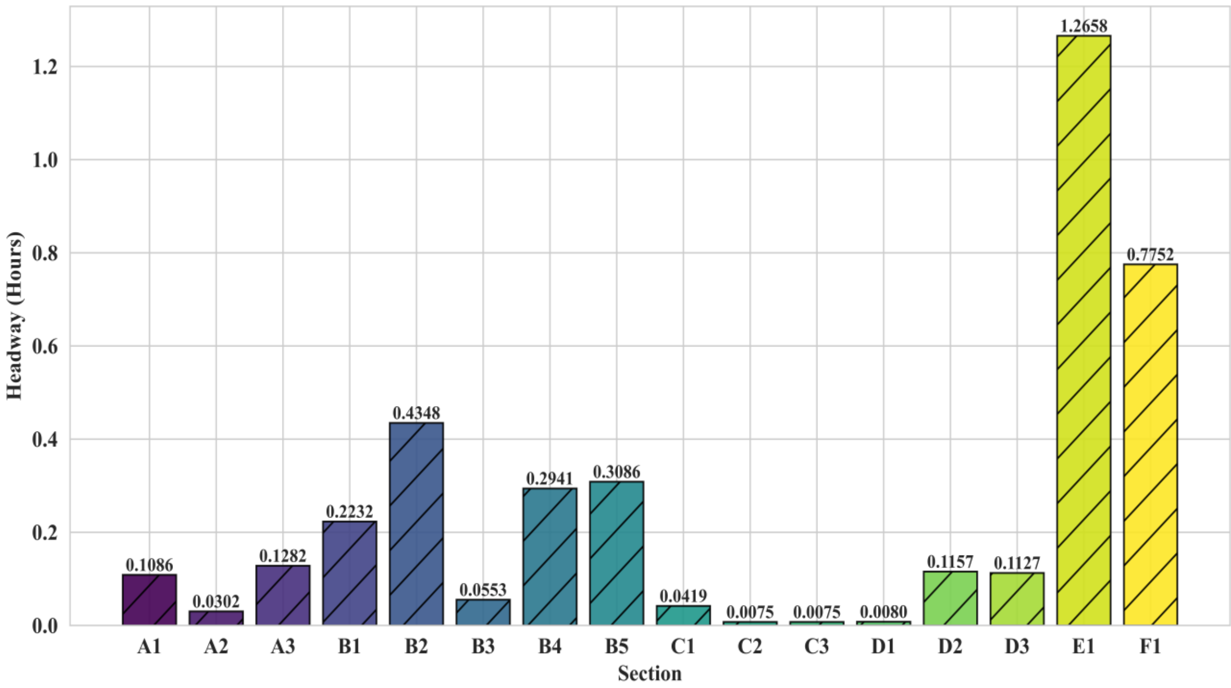


Figure 7. Headway Distribution with 50% Increased Heavy Vehicles

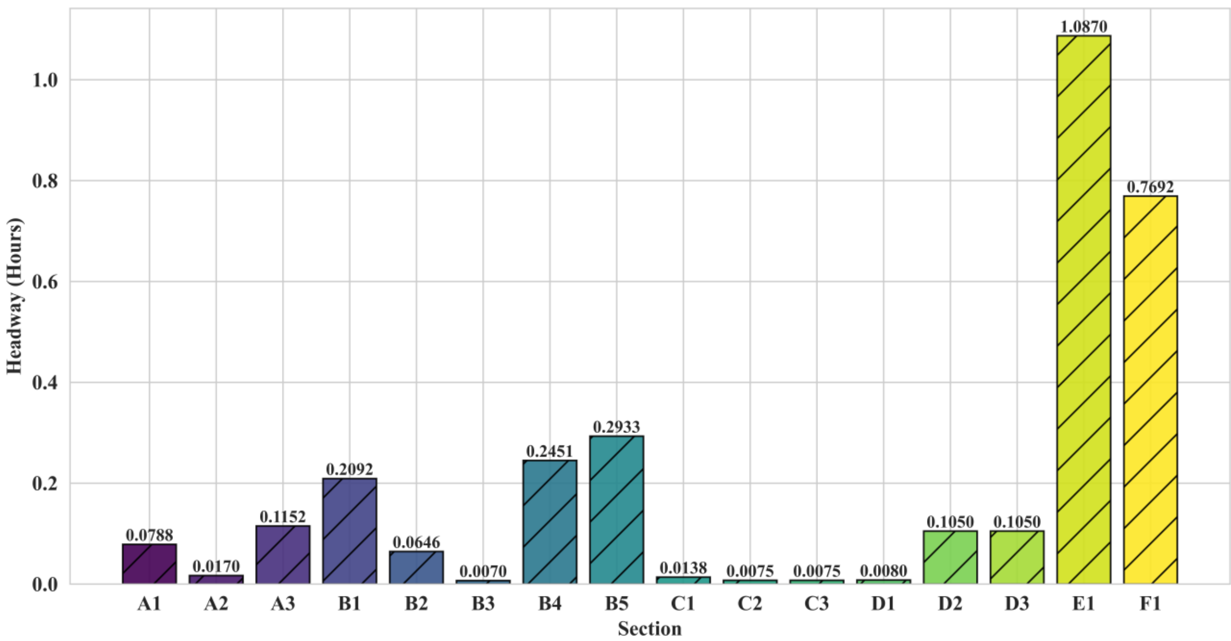


Figure 8. Headway Distribution with 100% Increased Heavy Vehicles

4.2. Delay Analysis

The results indicate a significant increase in total delay as the proportion of heavy vehicles rises. In the initial case, delays were relatively moderate across all sections, with noticeable congestion in certain areas due to existing traffic conditions. However, with a 50% increase in heavy vehicles, delayed values rose significantly, especially in sections C1 and C2, where freight traffic is prominent. The highest delays were observed in Case 3, with a 100% increase in heavy vehicles, causing extreme congestion in critical sections as shown in Figure 9.

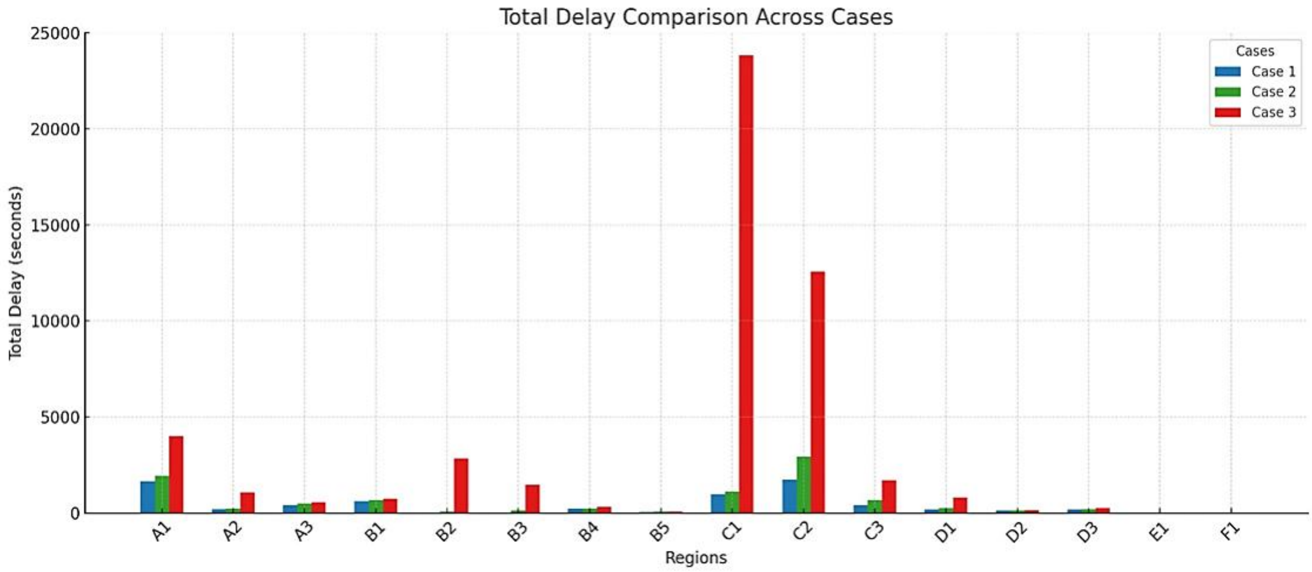


Figure 9. Total Delay Comparison Across Different Traffic Scenarios

As shown in Figure 9, sections C1 and C2 experienced the most substantial delay increases, exceeding 20,000 seconds in Case 3. This highlights the impact of heavy vehicle traffic on overall intersection performance, particularly in sections with high freight movement. Other sections, such as A1 and B2, also exhibited an increase in delay, though at a lesser magnitude. These findings emphasize the need for improved traffic management strategies to mitigate excessive delays caused by high heavy vehicle penetration.

4.3. Speed Analysis

The speed analysis across the three traffic scenarios demonstrates a clear correlation between increased heavy vehicle presence, congestion, and reduced vehicle speeds. In the initial scenario, higher speeds are recorded across most sections, with passenger vehicles maintaining steady speeds in less congested areas such as B5, E1, and F1. However, as shown in Figure 10, a 50% increase in heavy vehicles (Case 2) leads to noticeable speed reductions in sections B2, C1, and particularly C2, where congestion intensifies due to higher traffic density and longer vehicle clearance times. This interaction highlights that congestion caused by heavy vehicles restricts maneuverability and forces slower speeds as vehicle queues build up.

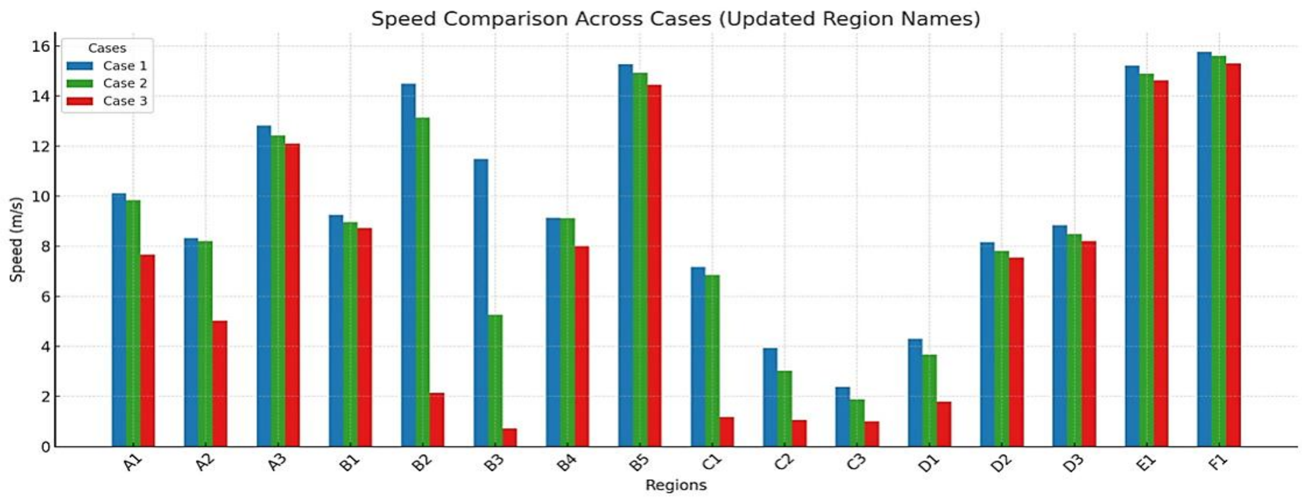


Figure 10. Speed Comparison Across Different Traffic Scenarios

In Case 3, where heavy vehicle presence doubles, the speed reduction becomes even more pronounced. Sections C2 and C3 exhibit the lowest speeds, coinciding with the longest delays and highest queue lengths observed in previous analyses. These results confirm that congestion and speed are inversely related — as traffic density and delays increase, vehicle speeds decrease sharply, especially in areas dominated by heavy vehicle interactions. On the other hand, sections E1 and F1 remain relatively stable across all scenarios, indicating that areas with less heavy vehicle interference experience minimal speed reductions. Overall, the analysis illustrates that heavy vehicle-induced congestion directly contributes to speed variability and traffic performance deterioration, especially in high-conflict zones.

5. Discussion

These results reveal important implications for intersection performance with escalating heavy vehicle proportions when it comes to headway, delay, and speed. Results reveal that the heavier vehicles there are, the worse the traffic efficiency, which impacts both heavy and passenger car movements.

Headway analysis: headway times Analysis (Figure 6, 7, and 8) demonstrates that traffic density increases as heavy vehicle penetration increases. Headways were stable in many sections in the initial case but sections E1 & F1 remained the most stable because of lower congestion. However, as the proportion of heavy vehicles increased by 50% and then 100%, headway times significantly decreased, especially in sections C2 and C3, where congestion intensified. This suggests that heavy vehicles disrupt traffic flow by requiring more space and time to accelerate and decelerate, leading to tighter vehicle spacing and greater risk of stop-and-go conditions.

Delay Analysis: The delay results (Figure 9) further emphasize the adverse effects of heavy vehicle presence on intersection performance. The delay increases significantly with higher heavy vehicle proportions, particularly in sections C1 and C2, which exhibit the highest levels of congestion. The increase in delay is most pronounced in Case 3, where the total delay time more than doubles compared to the initial case in critical sections. This sharp rise in delay indicates that heavy vehicles contribute to longer queue lengths and slower vehicle discharge rates, leading to overall traffic inefficiencies.

Speed Analysis: The speed comparison (Figure 10) demonstrates a direct correlation between heavy vehicle presence and traffic speed reductions. In the initial case, speeds were higher and more consistent across all sections, particularly in less congested areas such as B5, E1, and F1. However, as heavy vehicle proportions increased, speed declined significantly, with the most severe reductions occurring in sections C2 and C3, where congestion and vehicle interaction were highest. The decrease in speed aligns with the findings from headway and delay analyses, further supporting the conclusion that high heavy vehicle presence leads to traffic flow degradation.

Generally, the study demonstrates that highly effective traffic management techniques are required for intersections with high heavy automobile volumes. Results indicate that dedicated lanes, signal optimization, and alternative routing for heavy vehicles might decrease congestion at intersections. Future research might investigate such strategies to enhance traffic flow efficiency in similar urban/industrial corridor settings.

6. Conclusion

This research examined just how increasing heavy vehicle proportions impacts intersection performance in terms of headway, delay, and speed. Findings show that increasing the percentage of heavy vehicles reduces intersection efficiency, leading to heavy traffic congestion and operational difficulties. Headway analysis revealed that higher heavy vehicle proportions result in lowered following times, particularly in high traffic density sections like C2 and C3 indicating higher traffic pressure and reduced maneuverability for all vehicle types. Delay analysis confirmed that heavy vehicle presence adversely affected sections C1 and C2 where heavy vehicle penetration doubled the most. Lastly, speed analysis demonstrated that traffic flow is substantially disrupted by increasing share of heavy vehicles and hence slower total speeds in congested sections. These results recognize the need for traffic management interventions to relieve congestion at intersections with heavy automobile volumes. Strategies like dedicated freight lanes, optimized signal timing, and alternative routes for heavy vehicles might enhance intersection efficiency. Future studies can investigate their implementation in simulation and real-world applications to enhance traffic flow and minimize delays in similar urban and industrial corridors.

Acknowledgements

We would like to express our sincere gratitude to Çankaya University and the Department of Civil Engineering for their valuable support and guidance throughout the development of this research.

Declaration of Competing Interest

No conflict of interest was declared by the authors.

Authorship Contribution Statement

Mustafa Albdairi: Methodology, Writing – Original Draft, Reviewing and Editing
Zeynep Demirel: Data Preparation, Methodology, Writing – Review and Editing
Öykü Pehlivan: Data Preparation, Methodology, Writing – Review and Editing
Ece Esirgün: Data Preparation, Methodology, Writing – Review and Editing
Ali Almusawi: Supervision, Conceptualization

References

[1] A. K. Mohanty *et al.*, "Sustainable composites for lightweight and flame retardant parts for electric vehicles to boost climate benefits: a perspective," Compos. Part C: Open Access, vol. 12, Art. no. 100380, Oct. 2023, doi: 10.1016/j.jcomc.2023.100380.

[2] M. Albdairi, A. Almusawi, and S. S. S. M. Qadri, "Comparative conflict analysis of human-driven and autonomous vehicles at signalized intersections," Int. J. Automot. Technol., vol. 13, no. 4, pp. 180-190, Dec. 2024, doi: 10.18245/ijaet.1523772.

[3] M. Albdairi and A. Almusawi, "Examining the Influence of Autonomous Vehicle Behaviors on Travel Times and Vehicle Arrivals: A Comparative Study Across Different Simulation Durations on the Kirkuk-Sulaymaniyah Highway," Int. J. Automot. Technol., vol. 8, no. 3, pp. 341-353, Aug. 2024, doi: 10.30939/ijastech..1480916.

[4] Y. Pan, Q. Cheng, A. Li, J. Zhang, J. Guo, and Y. Chen, "Analysis of congestion key parameters, dynamic discharge process, and capacity estimation at urban freeway bottlenecks: a case study in Beijing, China," Transp. Lett., pp. 1-20, Sep. 2024, doi: 10.1080/19427867.2024.2404349.

[5] H. Alshibly and M. Mezher, "Bus Priority Signal Design and Control at Unconventional Intersections: A Simulation-Based Study in Jönköping," 2024. [Online]. Available: http://hdl.handle.net/20.500.12380/308067.

[6] S. R. Bonela and B. R. Kadali, "Examining the effect of vehicle type on right-turn crossing conflicts of minor road traffic at unsignalized T-intersections," IATSS Research, vol. 47, no. 4, pp. 545-556, Dec.2023, doi: 10.1016/j.iatssr.2023.12.002.

[7] J. Goyani, N. Gore, and S. Arkatkar, "Modeling Crossing Conflicts at Unsignalized T-Intersections under Heterogeneous Traffic Conditions," J. Adv. Transp., vol. 2022, no. 1, Art. no. 9965733, Oct.2022, doi: 10.1155/2022/9965733.

[8] S. R. Bonela and B. R. Kadali, "Review of traffic safety evaluation at T-intersections using surrogate safety measures in developing countries context," IATSS Research, vol. 46, no. 3, pp. 307-321, Oct.2022, doi: 10.1016/j.iatssr.2022.03.001.

[9] F.-j. Li, H.-w. Yang, R. Ayyamperumal, and Y. Liu, "Pollution, sources, and human health risk assessment of heavy metals in urban areas around industrialization and urbanization-Northwest China," Chemosphere, vol. 308, Art. no. 136396, Dec.2022, doi: 10.1016/j.chemosphere.2022.136396.

[10] H. Karimi, B. Ghadirifaraz, S. N. Shetab Boushehri, S.-M. Hosseininasab, and N. Rafiei, "Reducing traffic congestion and increasing sustainability in special urban areas through one-way traffic reconfiguration," Transportation, pp. 1-24, Feb. 2022, doi: 10.1007/s11116-020-10162-4.

[11] Z. Zhang and X. T. Yang, "Analysis of highway performance under mixed connected and regular vehicle environment," J. Intell. Connect. Veh., vol. 4, no. 2, pp. 68-79, Jul.2021, doi: 10.1108/JICV-10-2020-0011.

[12] I. Matalqah, M. Shatanawi, A. Alatawneh, and F. Mészáros, "Impact of different penetration rates of shared autonomous vehicles on traffic: Case study of Budapest," Transp. Res. Rec. vol. 2676, no. 12, pp. 396-408, Jun.2022, doi: 10.1177/03611981221095526.

[13] M. Graba, J. Mamala, A. Bieniek, and Z. Sroka, "Impact of the acceleration intensity of a passenger car in a road test on energy consumption," *Energy,* vol. 226, Art. no. 120429, Mar. 2021, doi: 10.1016/j.energy.2021.120429.

[14] A. Zuska, D. Kurczyński, and J. T. Jackowski, "Study of Loads Acting on the Load during the Sudden Braking of a Vehicle," Appl. Sci., vol. 13, no. 3, Art. no. 1559, Jan. 2023, doi: 10.3390/app13031559.

[15] J. Yarlagadda, P. Jain, and D. S. Pawar, "Assessing safety critical driving patterns of heavy passenger vehicle drivers using instrumented vehicle data–An unsupervised approach," Accid. Anal. Prev., vol. 163, Art. no. 106464, Dec.2021, doi: 10.1016/j.aap.2021.106464.

[16] S. V. Kumar, P. Priyadharshini, B. Dhanalakshmi, and K. Settu, "Study of traffic flow at a three legged busy intersection in vellore, india," IOP Conf. Ser. Mater. Sci. Eng., vol. 396, no. 1, Art. no. 012015, Aug.2018, doi: 10.1088/1757-899X/396/1/012015.

[17] X. Wang, P. Zhao, and Y. Tao, "Evaluating impacts of overloaded heavy vehicles on freeway traffic condition by a novel multi-class traffic flow model," Sustainability, vol. 10, no. 12, Art. no. 4694, Dec.2018, doi: 10.3390/SU10124694.

[18] P. Kesuma, M. Rohman, and C. Prastyanto, "Risk analysis of traffic congestion due to problem in heavy vehicles: a concept," IOP Conf. Ser. Mater. Sci. Eng., vol. 650, no. 1: IOP Publishing, Art. no. 012011, Oct. 2019, doi: 10.1088/1757-899X/650/1/012011.

[19] D. M. P. Wedagama, "The influence of mixed traffic on congestion level and marginal road congestions," *GEOMATE Journal,* vol. 17, no. 64, pp. 18-25, Dec. 2019, doi: 10.21660/2019.64.15106.

[20] B. Pan, S. Liu, Z. Xie, Y. Shao, X. Li, and R. Ge, "Evaluating operational features of three unconventional intersections under heavy traffic based on CRITIC method," *Sustainability,* vol. 13, no. 8, Art. no. 4098, Apr. 2021, doi: 10.3390/SU13084098.

[21] C.-G. Roh, H. Jeon, and B. Son, "Do heavy vehicles always have a negative effect on traffic flow?," Appl. Sci., vol. 11, no. 12, Art. no. 5520, Jun.2021, doi: 10.3390/app11125520.

[22] H. Sugari, A. Kusuma, and R. Y. Purnomo, "Impact of Overloading Vehicle towards the Level of Service on Freeway Segment (Case Study: JORR KM 27 to KM 23)," IOP Conf. Ser. Earth Environ. Sci., vol. 1000, no. 1: IOP Publishing, Art. no. 012019, Apr. 2022, doi: 10.1088/1755-1315/1000/1/012019.

[23] S. Singh and S. M. Santhakumar, "Assessing the impacts of heavy vehicles on traffic characteristics of highways under mixed traffic platooning conditions," Eur. Transp. - Trasp. Eur., vol. 3, May 2022, doi: 10.48295/et.2022.86.3.

[24] M. Albdairi, A. Ghazi, and A. Aldawoodi, "Impact of Aggressive HGV Platoons and Human-Driven Heavy Goods Vehicles on Signalized Intersections Performance," Int. J. Eng. Res. *(IJRISE),* vol. 4, no. 03, pp. 53-67, May 2024, doi: 10.55529/ijrise.43.53.67.

[25] A. Almusawi, M. Albdairi, and S. S. S. M. Qadri, "Assessing Traffic Performance: Comparative Study of Human and Automated HGVs In Urban Intersections and Highway Segments," Int. J. Integr. Eng., vol. 16, no. 5, pp. 409-427, Aug.2024, doi: 10.30880/ijie.2024.16.05.031.

[26] Z. A. P. Sari and G. Mauramdha, "Analysis of traffic flow due to lane changes by heavy vehicles," IOP Conf. Ser. Earth Environ. Sci., vol. 1294, no. 1, Art. no. 012026, Jan. 2024, doi: 10.1088/1755-1315/1294/1/012026.