

Original Article

Impact Analysis of Metro Rail Construction Work Zone on Travel Delay

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Abstract - Metro rail transit systems (i.e., urban and light rail) have impacts on the mitigation of congestion and sustainable development of urban traffic systems and its advantages in terms of speed, land occupation, and low emissions. There are many events where the current traffic lane is impacted by construction due to the metro rail project. Traffic flow operations on metropolitan roads are significantly impacted by work zones. Long-term work zones result in a number of traffic difficulties, including reduced capacity, increased delay, lower space mean speed, increased congestion, decreased LOS, and environmental problems, including noise pollution and deteriorating air quality, because they restrict the available lane width. The primary job-related work zone is designed for highway conditions, however the impacts of heterogeneous traffic in an urban area are highly varied. It also investigates the travel delay of roads during and after construction effects. The study indicates the reduction of delay observed after the construction.

Keywords - Available Lane Width, Construction work area, Delay in travel time, Free flow condition, Traffic composition.

1. Introduction

Cities are essential for fostering wealth and economic growth. Cities' institutional, social, and physical infrastructure is crucial to their sustainable growth. Transportation infrastructure is crucial in this situation. India's urban population has grown dramatically.

The proportion of the population living in cities has increased from 17% in 1951 to 35% in 2022. As a result, both the quantity and size of cities have grown significantly. Even though conditions vary greatly amongst Indian cities, there are some elementary patterns that influence transportation demand, such as a significant rise in urban population, household incomes, and industrial and commercial activity.

Construction activities often create situations where existing traffic lanes are affected or disrupted.

Furthermore, lane closures are occasionally necessary for a variety of work-related tasks. Significant effects on traffic conditions are caused by such activities, including decreased urban roadway capacities, extended travel time for road users, higher accident and fuel consumption rates, air pollution, and noise pollution.

Building a metro rail system is a long-term undertaking. The construction work area is the location that has the biggest impact on the current traffic situation. A work area is a section of road where construction or maintenance activities alter the operating features of traffic flow across the segment or interfere with one or more available lanes.

A construction work area is an area of a road where some construction, maintenance is being done. As seen in Figure 1, a construction work area is made up of the advance warning area, activity area, transition area, and work end area. In the developed countries most of the work zone delay studies were performed on uniform traffic conditions. However, limited research has been conducted in developing countries such as India under mixed traffic conditions involving vehicles of various sizes and operating characteristics.

2. Background of Study

To address traffic congestion issues and improve public transportation, many cities have introduced Metro Rail Systems as a fast, reliable, and sustainable mode of transport. While metro rail provides significant long-term benefits for urban mobility, its construction phase creates considerable disturbances to existing road traffic.



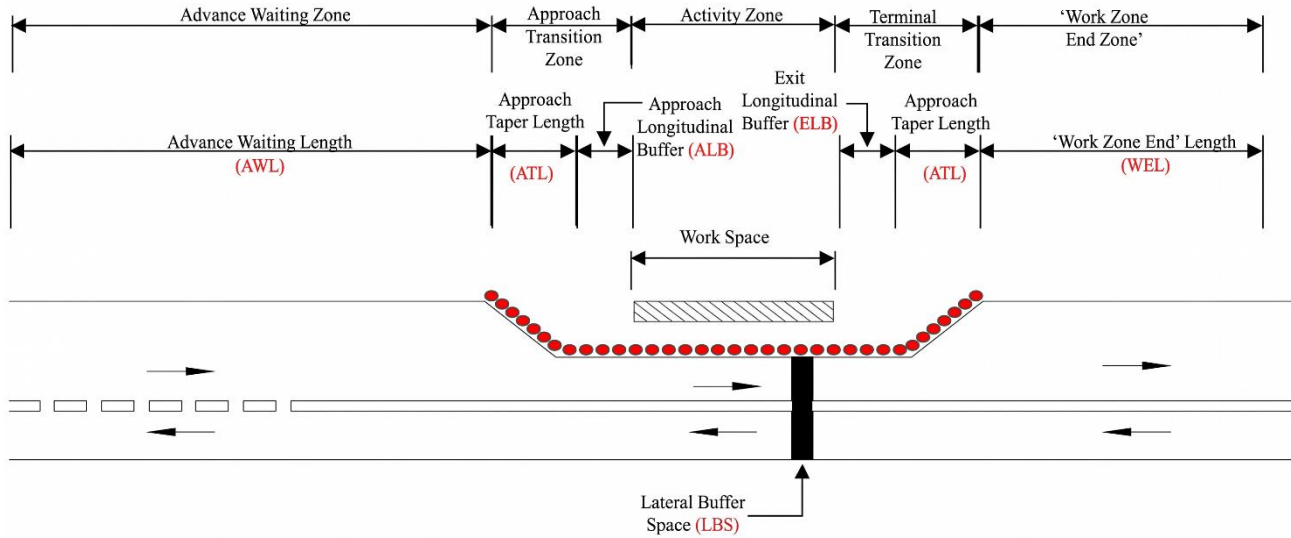


Fig. 1 Work area (Source: IRC SP 055, 2014) [1]

During metro rail construction, activities such as barricading, excavation, utility shifting, material storage, and temporary lane closures often reduce the available road space. These work zones interrupt the normal movement of vehicles and decrease the effective capacity of roads. As a result, commuters experience longer travel times, increased delays, traffic queues, higher fuel consumption, and increased air and noise pollution.

Delays in work zones are influenced by factors such as traffic volume, percentage of heavy vehicles, reduction in lane width, and length of the construction zone. Most research is conducted either on highways or in developed nations where traffic conditions are relatively uniform and disciplined. In contrast, Indian cities such as Ahmedabad experience highly heterogeneous involving two-wheelers, auto-rickshaws, cars, buses, and non-motorized vehicles sharing the same road space.

Research addressing the influence of urban rail projects under heterogeneous traffic conditions is still limited, particularly in the context of Indian urban roads. Therefore, it is essential to examine how such projects affect travel delays in mixed traffic environments. Understanding these impacts can support the development of effective traffic management measures and help reduce inconvenience experienced by road users during urban rail project activities.

3. Problem Definition

Rapid urbanization in Indian cities has led to a sharp increase in travel demand, putting heavy pressure on the existing road infrastructure. To address this growing mobility need, many cities are developing metro rail systems as an efficient mode of mass transportation. Although metro rail projects provide long-term transportation benefits, their construction activities often create major disruptions to

existing traffic conditions. During the construction phase, significant portions of road space are occupied by barricading, piling operations, material storage, utility shifting, and lane closures, forming temporary work zones along urban corridors. These work zones disturb the normal movement of traffic and reduce the effective roadway capacity, particularly on busy urban arterials carrying heterogeneous traffic streams. As a result, commuters frequently experience increased travel time, larger delays, excessive fuel consumption, air pollution, and travel discomfort. The situation becomes more critical in Indian traffic conditions due to the mixed traffic composition, varying vehicle characteristics, and irregular driving behavior.

Most of the delay prediction models have been created for freeway conditions or homogeneous traffic environments, and so they may not properly reflect the complex traffic conditions observed on Indian urban roads. So, it is needed to systematically study and evaluate the effect of construction work areas for traffic delays where mixed traffic is observed.

This study aims to identify the main factors influencing delay, such as traffic volume, percentage of heavy motor carriages, lane width reduction, and work area length, and to develop a practical and reliable delay estimation model for urban corridors impacted by construction activities of metro project.

4. Literature Review

Delays lower the excellence of carriageways because they are inconvenient. When drivers take longer than anticipated to complete a trip, it is known as a delay. There are numerous types of delays depending on different conditions. It comprises halted delays and operational delays brought on by cars slowing down in traffic. Delays are caused by several circumstances, including significant pedestrian traffic, mixed traffic, on-street parking, congestion, and inadequate

roadway and traffic conditions on automobile performance, heavy vehicle speeds, and delays were analysed as separate parameters. When computing delay by Equation (2), many reasons were considered, incorporating speed fluctuation, lane width, and difference in speed between cars and large vehicles [3].

$$EDV = V \times (1 + PHV \times (D_PCE - 1)) \quad (2)$$

In passenger cars, Equal-Delay-Volume (EDV) depends on diverse traffic volume V (veh. /hr), PHV = proportion of heavy vehicle and delay. To accommodate both motorized and non-motorized traffic, most urban regions are building multimodal facilities.

Due to this, system of transportation is susceptible to complex user and mode interactions. It is challenging to evaluate and characterize these intricate interactions consistently. A platform of microsimulation is needed to anticipate future conditions and mimic such real-world scenarios.

Using Vissim, a traffic model program, Kodupuganti & Pulugurtha investigated the impact of mixed traffic situations involving light rail transit, pedestrians, bicycles, and motorized traffic on intersection delays. The 2018 traffic scenario (without Light Rail Transit and NMT) was replicated to create the base simulation model. They suggested a framework to help planners evaluate how adding a new transit system, such as LRT, and related non-motorized traffic will affect the urban corridor [4].

To gather information from ordinary road users, a field survey technique that involved distributing forms, executing volume count surveys, and keeping track of vehicle speed, delay and travel time all day long. The study's findings indicate that congestion is being caused by too many cars, narrow streets, inadequate public transportation options, and the behavior of bus drivers, which causes drivers to experience extreme stress [5].

Traffic demand significantly decreased during COVID-19 epidemic, which led to large reductions in emissions, consumption of energy, and traffic delays. The potential environmental benefits of fewer cars on the street network were investigated. Microscopic modeling was conducted to simulate traffic at seven distinct networks. They concluded that, especially in crowded urban areas, lower traffic demand significantly reduces delays and emissions [6].

4.2. Methods for Estimating Delay

The traffic flow and information on spatiotemporal work zones on major Korean highways, Chung et al. devised an approach to predict traffic congestion induced by freeway construction zones [7]. A graphical technique based on Lighthill and Whitham's traffic shock-wave theory was utilized to evaluate filtering movement and to calculate

individual as well as overall delays [8]. Studies on prediction of journey time have shown how useful and important it is for making sensible travel plans and easing traffic. Existing models require accurate traffic data, especially traffic conditions, to estimate journey time. Passenger travel plans will be impacted by this. To depict traffic conditions, congestion in urban regions and taxi flow, the model have been developed and employed trajectory and traffic condition data. To increase the model's accuracy, they incorporated the time of departure and trip date. In terms of journey time prediction, the results state that models have certain benefits over some traditional models [9]. Anusha et al. assessed the time of travel in the mid-block portion of urban arteries. Travel time was anticipated using a speed-based weighted average approach, while model formulation techniques were applied to analyze the effects of traffic heterogeneity and poor lane discipline within mixed traffic conditions [10].

City road networks face unique challenges during disasters, necessitating their availability despite partially obstructed roads. Accurate journey time predictions on these roads are crucial, yet existing models derived from intact highways often yield erroneous estimations, adversely affecting traffic planning and emergency responses [11].

A thorough and accurate estimate of traffic delay resulting from a traffic lane work zone, where lanes on one direction is blocked, the traffic is diverted to share the road width in the opposite direction, was provided by Martinelli & Xu. The two sections of the total delay were the congestion delay and the speed reduction delay. They designed a procedure to find the journey delay due to daily congestion and created a model to find the queue in work area [12].

A triangular fundamental diagram was employed to illustrate the Kinematic Wave theory, while self-organized criticality was used for traffic flow analysis. The findings indicated that traditional traffic management methods are important for improving traffic operations [13].

Liu & Gayah devised a Max Pressure algorithm to oversee a transportation network having signalized crossings, known for its scalability and ease of implementation. The algorithm employs a point queue model, which represents vehicle transitions, not considering vehicle locations, which can influence control performance [14]. To achieve sustainable transportation, that is crucial to utilize underused road capacities to alleviate congestion on overused links while maintaining optimal system flow. Built on the deviation as well as relative departure of connection volume from matching capacity, Bayraktar suggested four methods for mitigating congestion [15].

Estimating delays and time of travel on arterial links using information of vehicles' positions is challenging, particularly with low sampling frequencies. Meng & Wang addressed this

by analyzing 30-second AVL data from transit buses, dividing travel time into free flow, congestion, and stopping time [16]. When traffic cannot be redirected, freeways must be rebuilt and restructured due to rising congestion levels. Simulation of traffic conditions is favored over Highway Capacity Manual methods for analyzing freeway reconstruction, as HCM cannot adequately assess user delays during construction. Each strategy to decrease user costs tends to increase direct reconstruction costs, highlighting a trade-off.

Astarita et al. examined delays on two-lane freeways with one lane available, utilizing a custom model for microscopic simulation to evaluate delays across various flow values and reconstruction of lengths [17]. By identifying the influence on the speeds of vehicles operating within designated work areas, Chitturi & Benekohal suggested calculating the capacity-at-operating-speed using the speed and flow curves created for work zones [3].

On freeways having maintenance operations, work zone-related traffic interruption is a significant cost factor. Chien et al. developed a method to estimate delays by limited simulation data using the CORSIM model. Additionally, by considering different geometric circumstances and temporal traffic distribution [18]. Benekohal carried out a statewide review and found that lane leasing and incentive/disincentive schemes were more successful in cutting down on construction zone duration and delay.

Road user costs were estimated using QUEWZ and spreadsheets; volume was estimated using the HCM method, while queue length and delay was evaluated with the QUEWZ tool. The developed methodology was further applied to determine capacity, delay, reduction in speed, queue length, and overall user costs [19]. A system is required to minimize travel times in work zones, as peak travel periods lead to congestion. Advanced Traveler Information Systems (ATIS) can provide real-time updates on delays and alternative routes.

A study by Reinolsmann et al. involving 80 drivers examined route choices based on travel updates shown on VMS and GRIP. GRIPs, offering visual maps of routes, were found more effective than VMS; 74-83% of drivers opted for an alternate route when zero delays were displayed. Moreover, when overall journey time was equal, GRIP system encouraged approximately 25% more drivers to choose the alternate route compared to VMS. [20] Travel time can be measured using a variety of methods. Two distinct approaches are commonly utilized to gather trip time delay data over a highway network: floating cars and loop detector-based techniques. Wang employed both loop detector-based techniques [21].

The rise in mobile phone usage globally is driving investigations into their role in huge data collection for various sectors, particularly transportation. Congestion is now a major issue, Fulponi proposed the cell phones use for traffic data. Integrating GPS and GIS enables detailed analysis of movement patterns, origins, and routes. The methodology for planning to alleviate congestion has been shown to be replicable [22].

For traffic management, travel time is crucial. More reliable trip timing information has been achieved using Automated Vehicle Identification systems. Recent advancements involve using Bluetooth and devices based on Wi-Fi-based for cost-effective travel time information, especially in city areas.

Ma et al. developed a trip time estimation system utilizing both internet and historical data to address system latency from vehicle re-identification. Testing of data demonstrated strong prediction performance, effectively capturing congestion trends. [23] A GPS-equipped test car was utilized to obtain data related to journey time and traffic delays. They created maps showing journey time, road network surrounding a reference point for a specific amount of time [24].

Table 1. Parameters for delay in work zone

Reference	Parameters for Work Zone Delay	Method/Approach/Tool
Meng et al. [16]	Travel times for free flow, traffic, and pausing at signalized junctions	Probabilistic approach
Astarita et al. [17]	Segment of length at free road segment, traffic flow, work area layout, the proportion of heavy vehicles, speed of light vehicles, and speed of heavy commercial vehicles.	Microscopic simulation model
Meng & Weng [2]	Heavy vehicle proportion, length of the transition area, traffic flow, and work zone configuration.	Heterogeneous Cellular Automata (HCA) model
Chitturi & Benekohal [3]	Carriageway width, speed fluctuations, and disparities between automobiles and speed of heavy commercial vehicle.	Input-output method based on the relationship between speed and flow
Lee et al. [26]	Work zone duration, work zone activity, intensity of work zone, speed, volume, lane closure position, and time.	Work Zone Capacity Analysis Tool (WZCAT) analytical software program
Chien et al. [18]	Work zone length, queue length, Flow, speed.	Simulation using CORSIM

Vyas T. and Varia H. evaluated traffic flow and speed, model during and after metro construction. The validated flow model reported construction-stage flow reductions ranging from 1% to 11% and identified available lane width, mean speed, and vehicle composition as key influencing factors [25].

In this work, delay has been estimated using regression analysis. Table 1 summarizes the several methods and factors utilized in delay analysis and modeling.

5. Research Gap

Most previous studies of impacts on travel delay and construction areas have been conducted in developed countries under homogeneous traffic conditions. However, Indian cities experience highly heterogeneous traffic, where different vehicle types share limited road space, making foreign models less suitable for direct application.

Research focusing on metro rail construction work areas is scarce, especially for large-scale and long-term urban infrastructure projects. Existing studies mainly focus on freeways and highways rather than congested urban arterial roads with intersections and significant side-friction activities.

Factors such as lane narrowing, barricading, roadside parking, pedestrian movement, and traffic diversions greatly influence the flow of traffic in Indian urban regions but are often not covered in existing delay models. Moreover, many models are location-specific and may not precisely depict the conditions in cities like Ahmedabad.

Hence, it is needed for field-based empirical studies using actual traffic and journey time data to develop reliable delay prediction models suitable for Indian urban mixed traffic conditions.

Table 2. Comparison of study

Study	Traffic Type	Study Area	Method	Limitation	Present Study Contribution
Meng & Weng (2011)	Homogeneous	Freeway	HCA Model	Highway conditions	Mixed urban traffic
Chitturi & Benekohal	Homogeneous	Work zones	Speed-flow relation	No metro corridor analysis	Metro rail corridor analysis
Present Study	Heterogeneous	Ahmedabad Urban Corridor	Field-based regression	-	During & after construction comparison

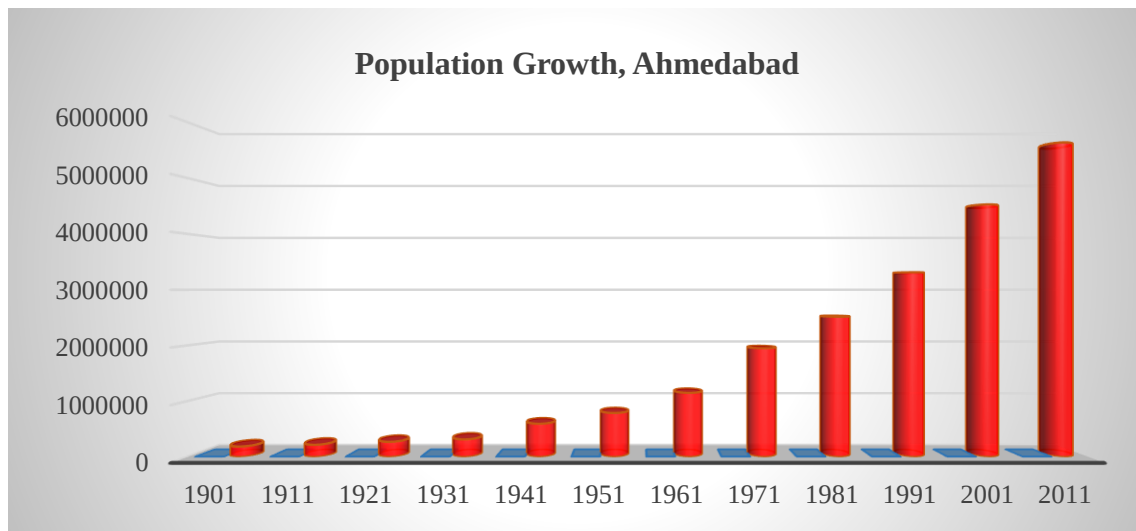


Fig. 3 Ahmedabad population growth (Source: Ahmedabad municipal corporation)

6. Study Area, Data Collection & Methodology

6.1. Study Area Selection

The current study is being conducted along a busy road in Ahmedabad, India. With a 464 km² land area and a 2600 km road network, Ahmedabad is the seventh largest city in India. Ahmedabad's population growth can be seen in Figure 3. In a

similar vein, traffic density is rising daily. There are 26 lakh cars in the city, growing at a rate of 2.19 lakh each year. Over the past 20 years, the number of automobiles in the city has increased dramatically; as of March 31, 2020, there were almost 49 lakh registered vehicles, of which more than 70% were two-wheelers. Figure 4 shows the vehicle growth in Ahmedabad.

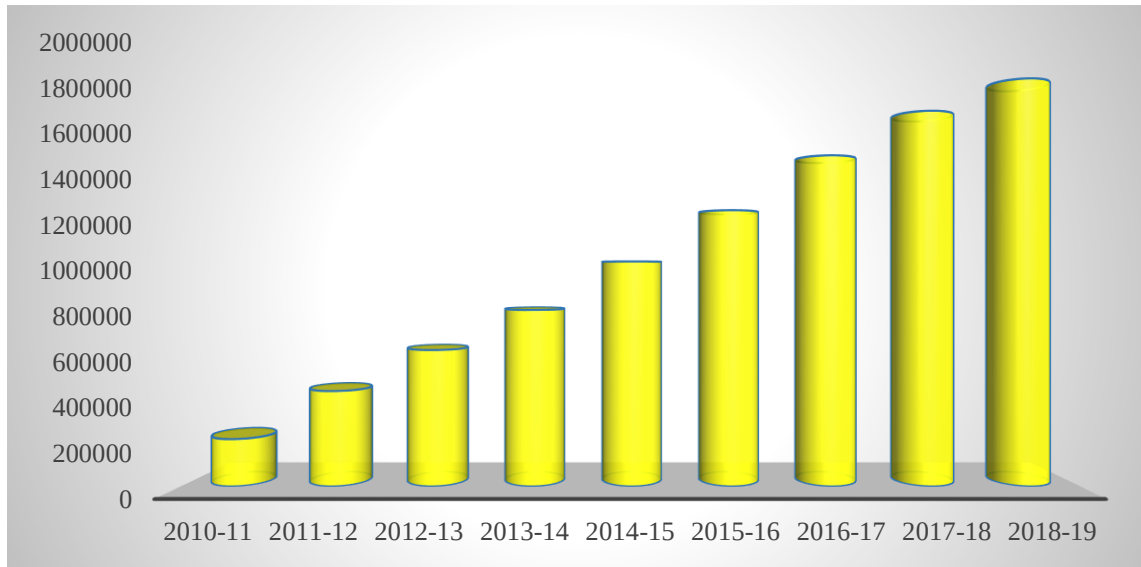


Fig. 4 Ahmedabad vehicular growth

Source: http://rtogujarat.gov.in/statistics_vehicle.php

6.2. Site Selection Justification

Some of the north-south corridor's portions, such the one from APMC to Paldi, had construction completed in 2017, while the remaining portion was on railway property, so the current traffic was not affected. The east-west metro corridor connecting Thaltej and Stadium Road was initiated in 2017 and was mostly completed in 2022. This corridor was considered suitable for comparing traffic performance under construction and post-construction conditions.

For data collection, a 6.2 km section extending from Stadium intersection to Thaltej intersection was selected, as presented in Figure 5.

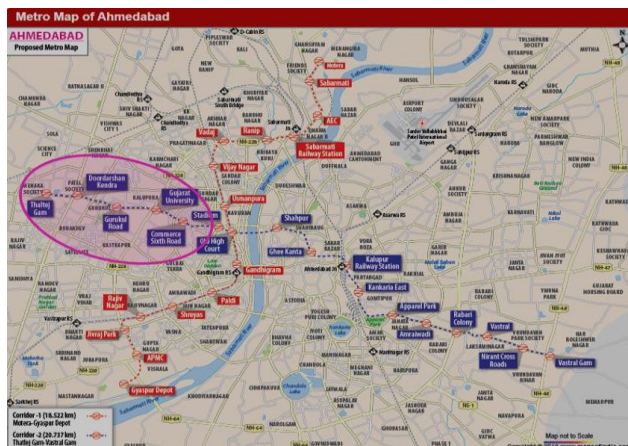


Fig. 5 Metro rail route map [27]

The selected corridor is bordered by both residential and commercial developments. Owing to the barricading associated with metro rail construction activities, portions of the roadway were obstructed at multiple locations, resulting in

variations in the effective lane width throughout the study stretch. For systematic data collection, the entire corridor was divided into seven individual links. Details of each link, including link name, available lane width, average building height, traffic volume per five minutes, and observed average values, are presented in Table 3.

6.3. Methodology for Data Collection

The methodology used in this study includes gathering information on how construction activity zones impact the study area's capacity. During the time of partial lane closures due to metro rail construction, data were collected. Data were then gathered to assess the impact following the elimination of the barricades.

Work zone limits, travel time, and delay surveys have been utilized to quantify the delay due to construction. First, early in the morning, when free flow conditions are available, the journey time under these conditions has been measured. According to Indo HCM (2017) standards, a vehicle traveling at a time headway of eight seconds or greater is deemed to be driving in free flow conditions. On the chosen links, this condition was acquired early in the morning. Travel time observations were carried out during morning peak hours, evening peak hours, and off-peak noon periods. Travel time delay was determined by the difference between free-flow travel time and the travel time recorded during peak and off-peak conditions.

Delay analysis was performed for all categories of vehicles during both the construction and post-construction phases [28]. Traffic delay measurements were obtained through a license plate survey conducted during morning peak, midday, and evening peak periods. Free-flow journey

time was additionally recorded at 6:00 a.m., when traffic movement was relatively uninterrupted. The corridor

exhibited significant variations in available carriageway width, as presented in Table 3.

Table 3. Road inventory data

Link No.	Link name	Length (m)	Available one-way carriageway width during construction (m)	Available one-way carriageway width after construction (m)
1	Thaltej to Sal	455	6	11.5
2	Sal to Gurukul	1000	7.5	11.5
3	Gurukul to Helmet	205 445	3.3 5.5	12
4	Helmet to Saurabh	250 230	5 7.7	11.3
5	Saurabh to Vijay	215	5	11.3
6	Vijay to Commerce	397 76 107	6 4.4 3.3	10
7	Commerce to Stadium	700	3.5	7.1

Table 3 shows that the carriageway widths of the links. Link-1 to link-4 have almost same carriageway width, while link-6 and link-7 have lesser width.

The total study corridor length is nearly 6.2 km long. The collective link length presented in this table is 4.08 km, as road intersections were excluded from the travel-delay analysis. Delay for these sections are considered as stop delay rather than link travel delay.

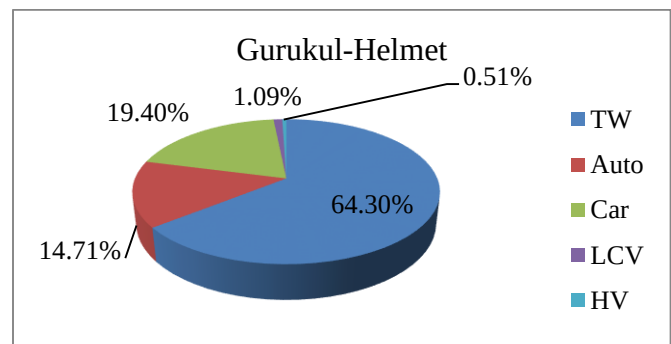
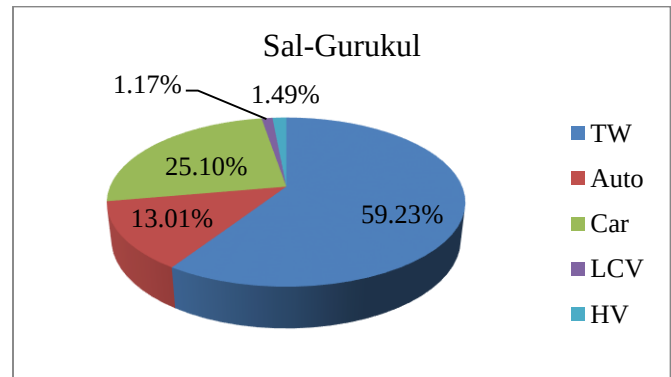
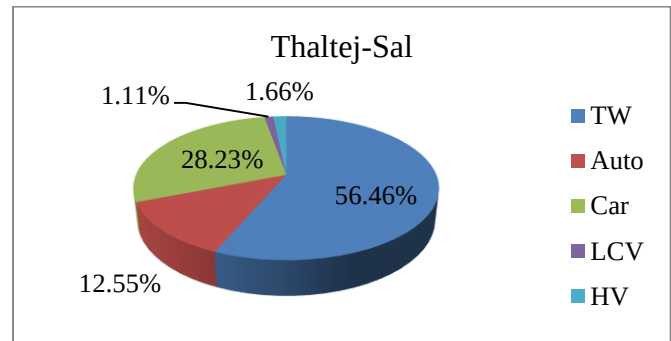
6.4. Sample Size Calculation

Sample size refers to the number of observations chosen to represent the overall population. The selection of an adequate sample size is essential for obtaining reliable statistical results. A very small sample may not represent the population properly, while an excessively large sample increases time and cost.

$$S = (z^2 \times p(1 - p)) / \varepsilon^2 \quad (3)$$

s = sample size for infinite population, z = Z score, = proportion of population (0.5), ε = error, for 95% confidence level and 5% margin of error, a minimum of 384 samples is required for an infinite population. In this study, actual observations exceeded this value. Traffic volume surveys were conducted at intervals of three minutes during morning peak, noon, and evening peak hours. More than 10% of the traffic volume was considered for collecting travel time and speed data for each vehicle category under both construction and post-construction conditions. The study included 1,529 traffic volume observations and 1,074 travel time observations.

Vehicle composition along each link was identified through videographic analysis, and the corresponding vehicle distribution is presented in Figure 6.



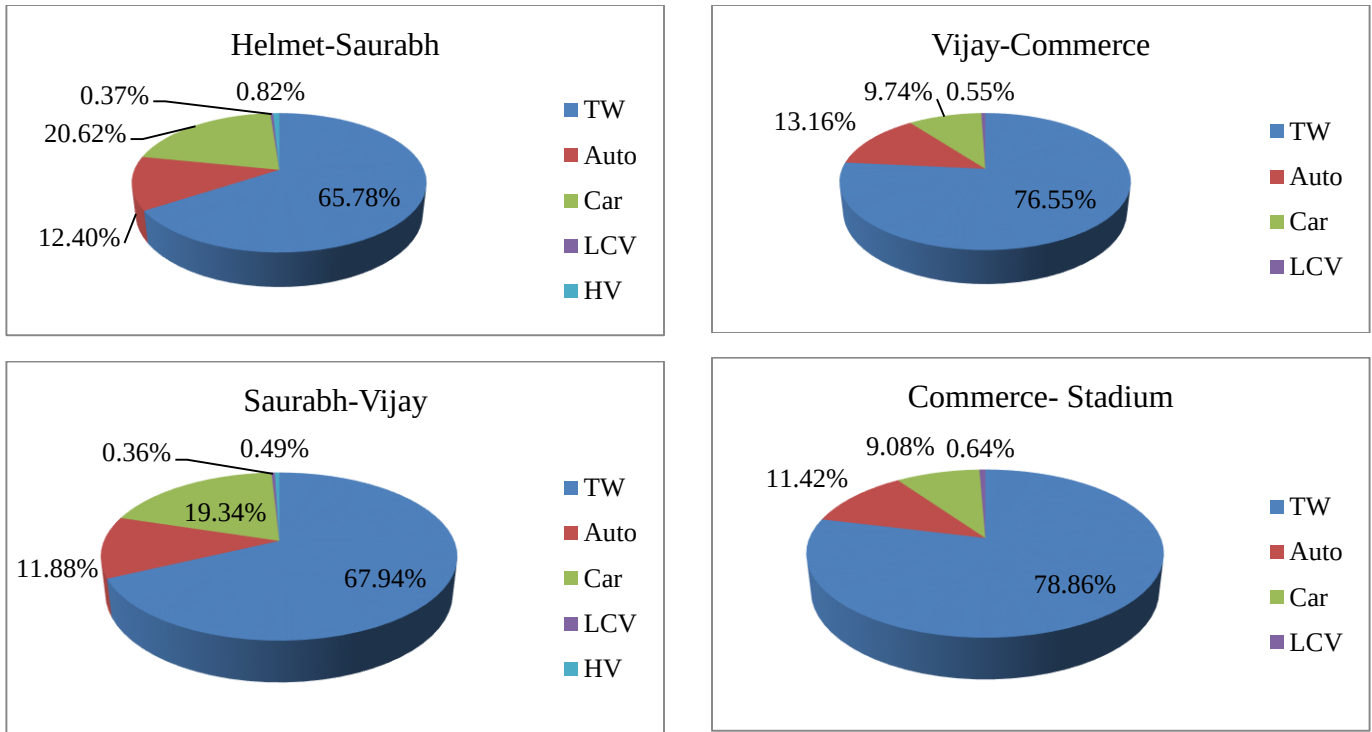
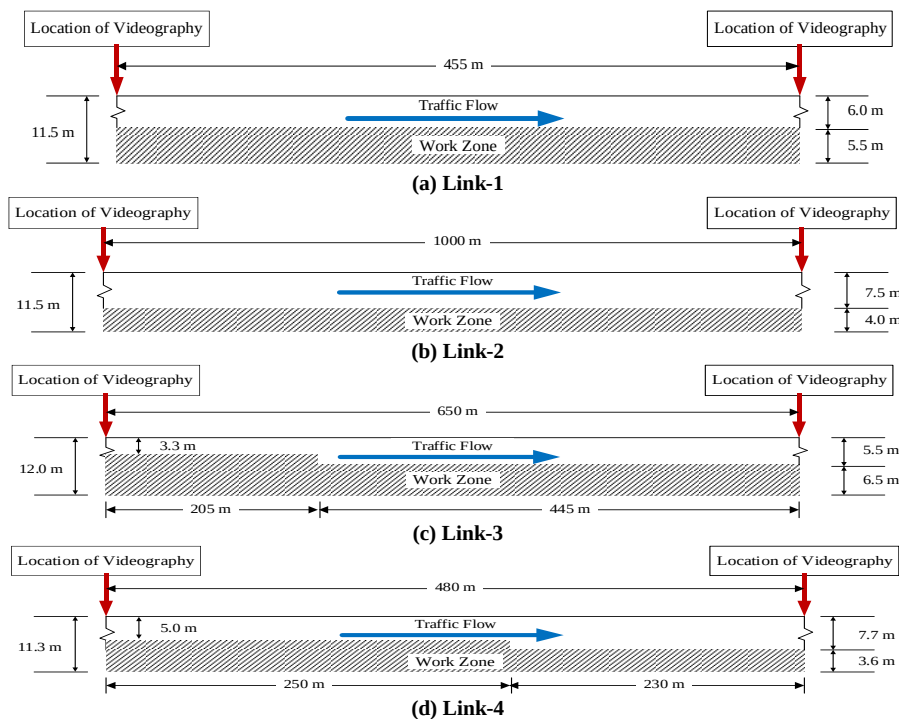


Fig. 6 Composition of vehicles during construction

Figure 6 indicates that two-wheelers contribute the highest proportion of traffic, while cars and auto-rickshaws form the next major categories. Large vehicles like buses and HVs were not allowed on the connections, which are Vijay Crossroads to Commerce Crossroads and Commerce Crossroads to Stadium Crossroads. The research area's

available carriageway width varies. The link's layout in the study area is depicted in Figure 7

The available road width of links varies significantly between Thaltej and Stadium intersection. The arrangement of links are shown in Figure 7.



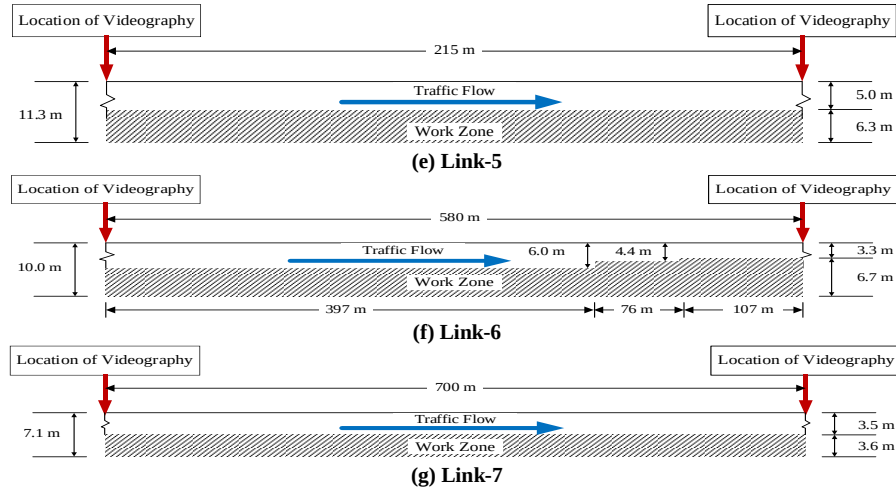
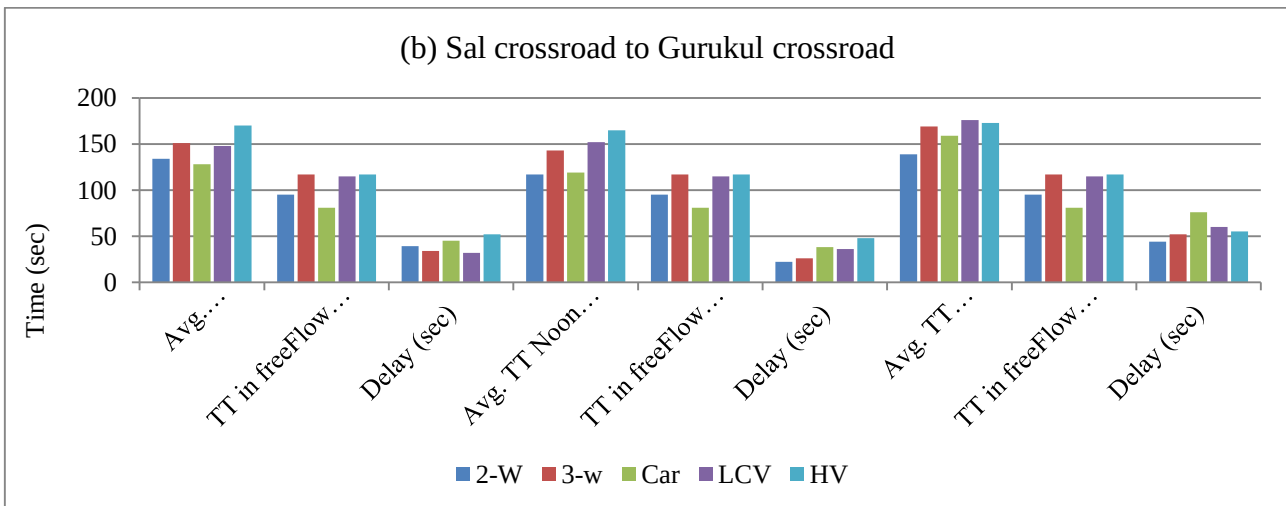
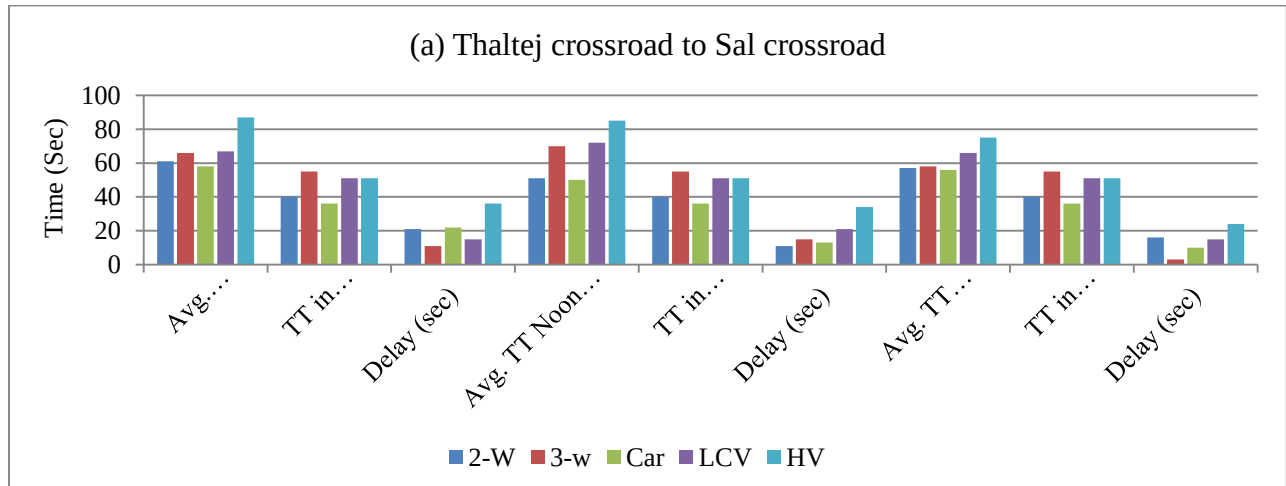


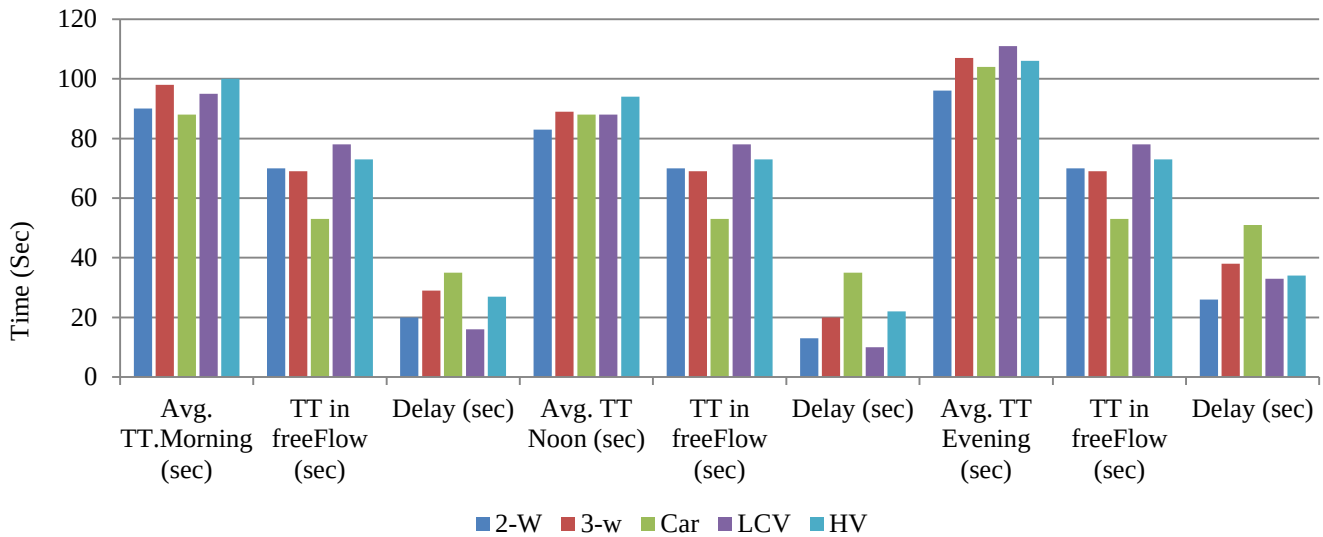
Fig. 7 All of the links' layout [27]

As can be seen in Figure 7, the road width of the connections between the Saurabh and Vijay crossroads and the Commerce and Stadium crossroads is the same. The linkages between the Gurukul and Helmet crossroads and the Helmet

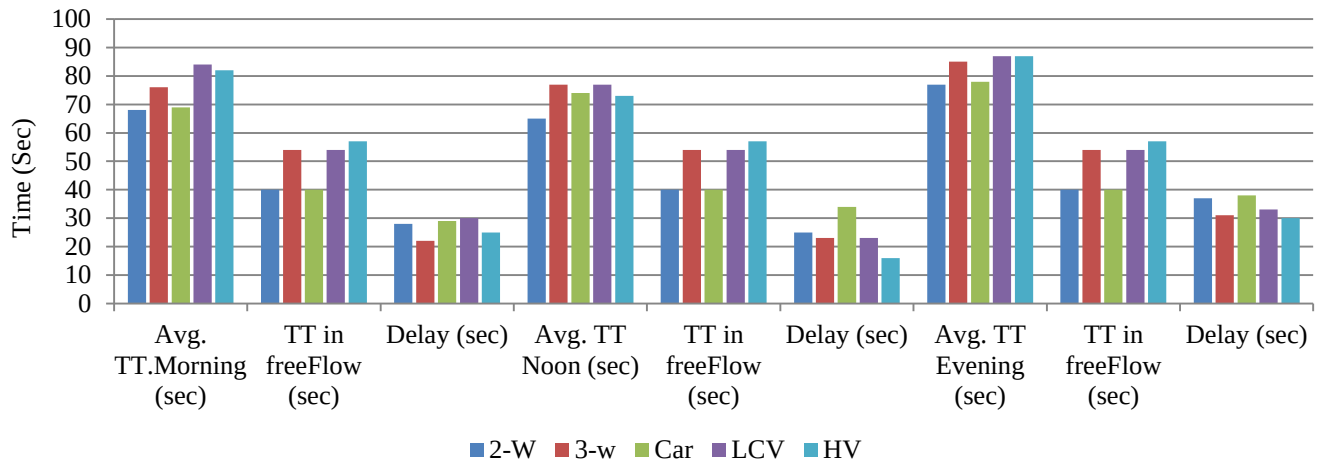
and Saurabh crossroads are two distinct widths. There are three distinct widths in the link-6. On all the segments, travel time information has been gathered. In the research area, Figure 8 displays travel time and delays.



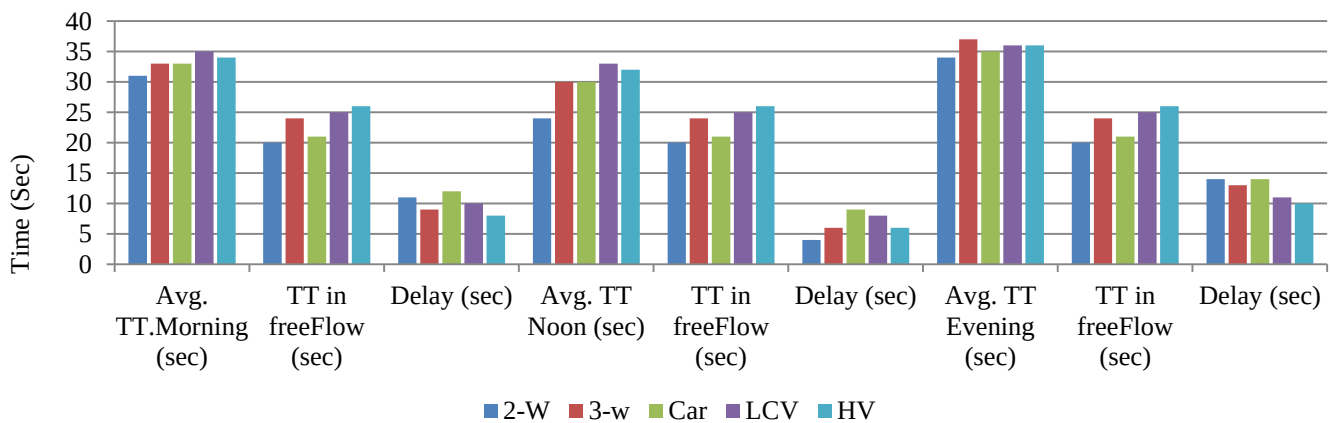
(c) Gurukul crossroad to Helmet crossroad



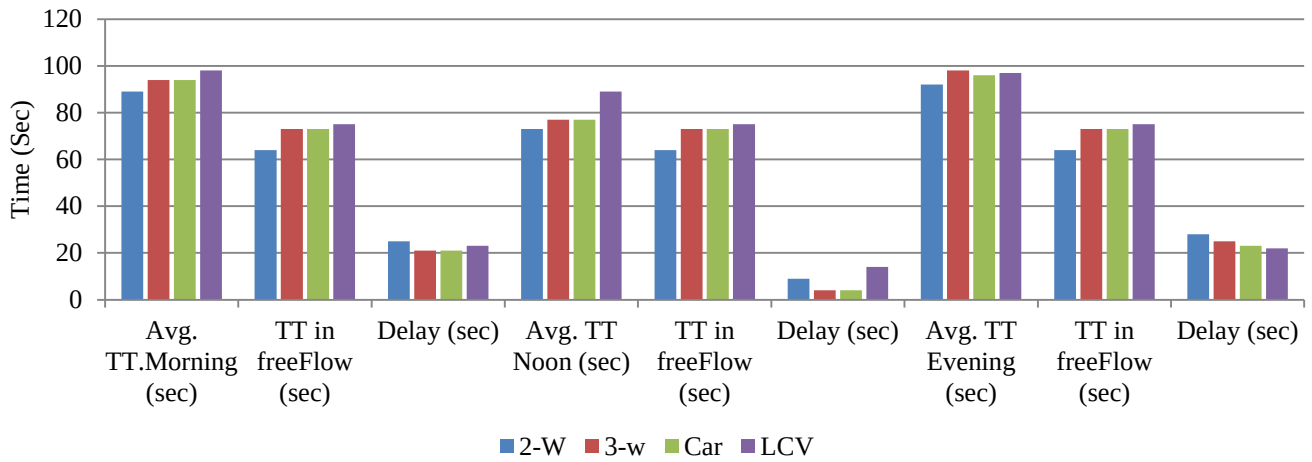
(d) Helmet to Saurabh crossroad



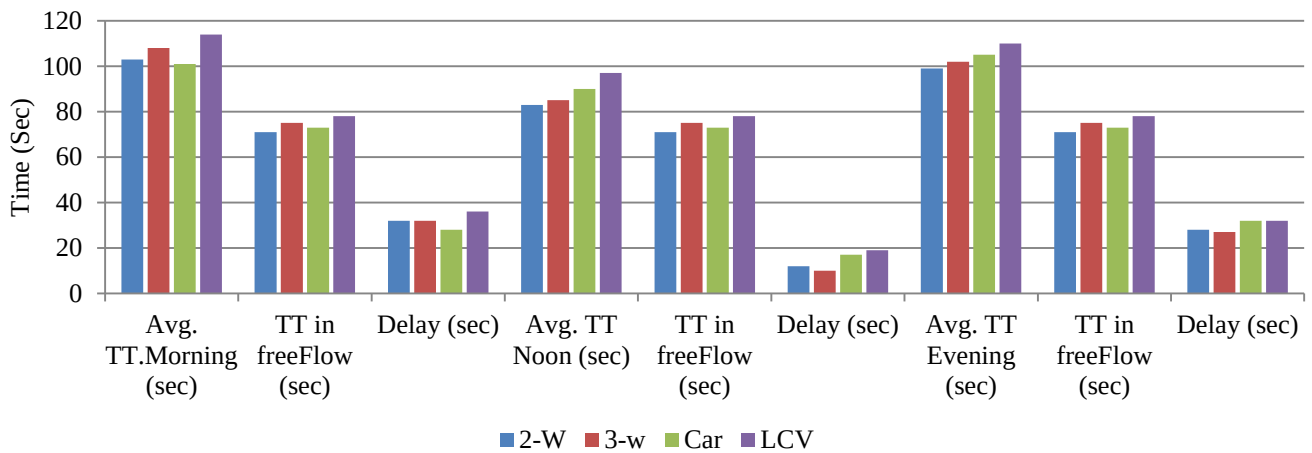
(e) Saurabh crossroad to Vijay crossroad



(f) Vijay crossroad to Commerce crossroad



(g) Commerce crossroad to Stadium Crossroad



(h) Observed average delay on each link during construction stage

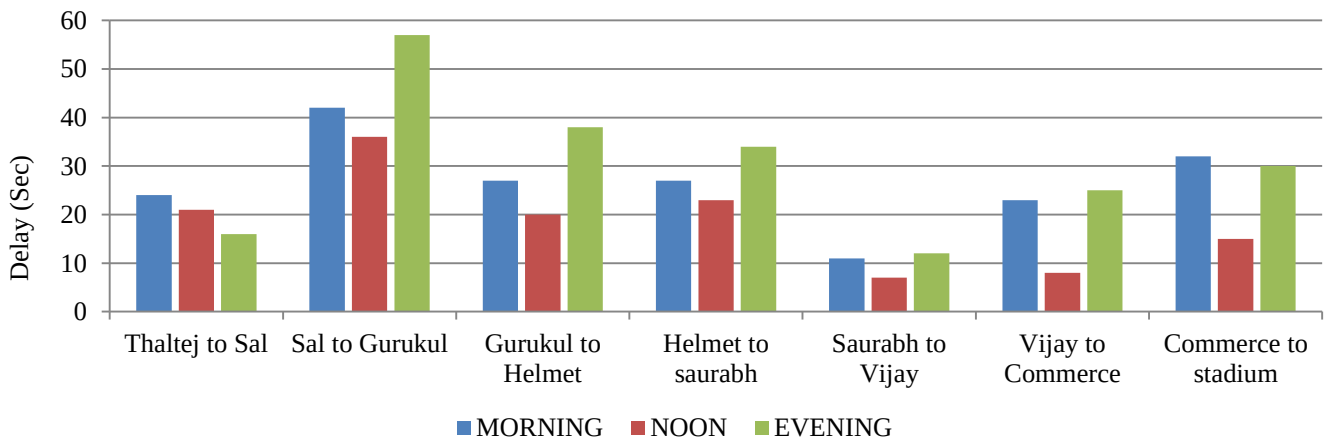


Fig. 8 Delay and time of travel during construction phase [27]

Figures 8 (a) to (g) illustrates the travel time and delay characteristics during the construction stage. Delays were found to be higher during evening peak hours and lower during noon-time off-peak periods across all links.

As shown in Figure 8 (h), the highest delay occurred on Link-2, i.e., Sal to Gurukul, during the evening period. The presence of commercial activities and shopping centers along this stretch contributed to heavy customer movement and increased traffic congestion.

The delay analysis considered the length of the construction area; however, only moving delay had been evaluated, excluding stopped delay. Average speed was used as an effective parameter to represent traffic performance. Figure 9 shows the average speed on different links during construction. The highest average speed of 26.00 km/h was observed on the Thaltej–Sal section, whereas the Helmet–Saurabh stretch exhibited the minimum average speed of 22.40 km/h.

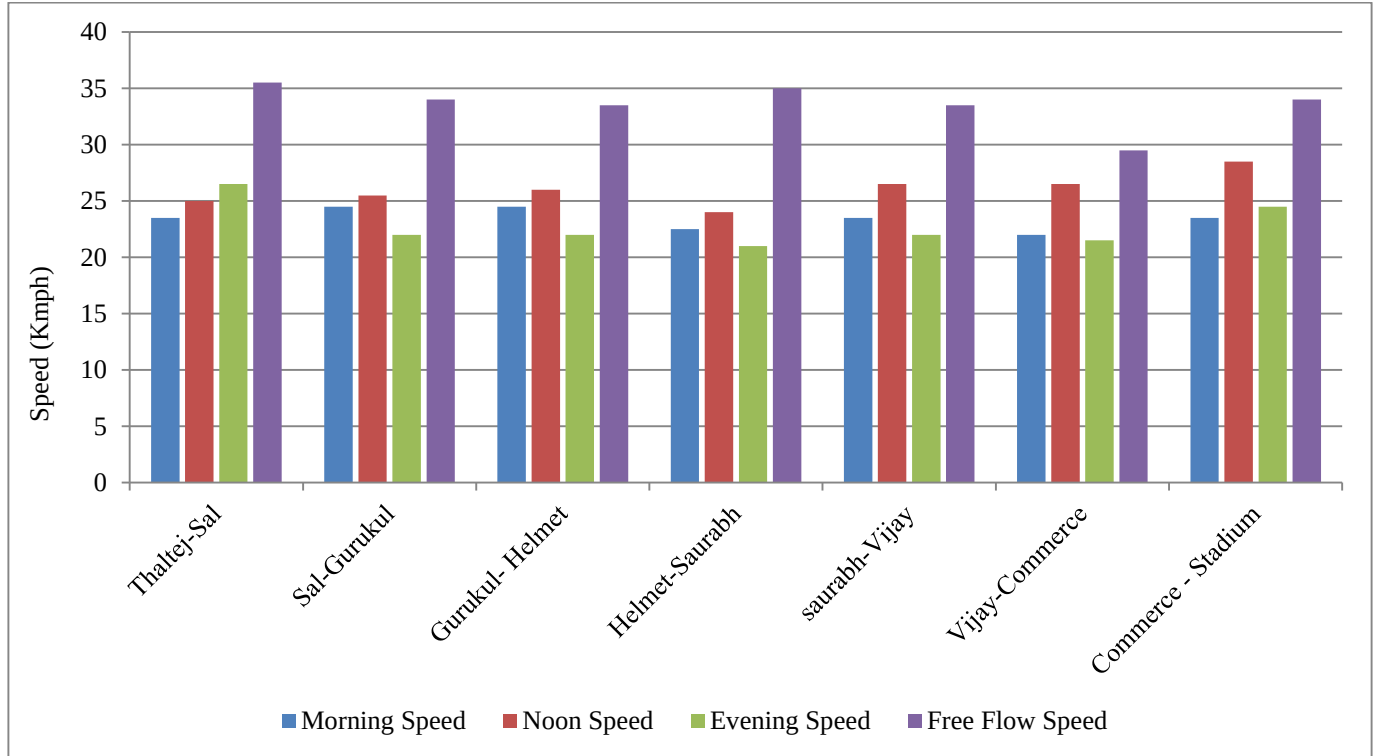
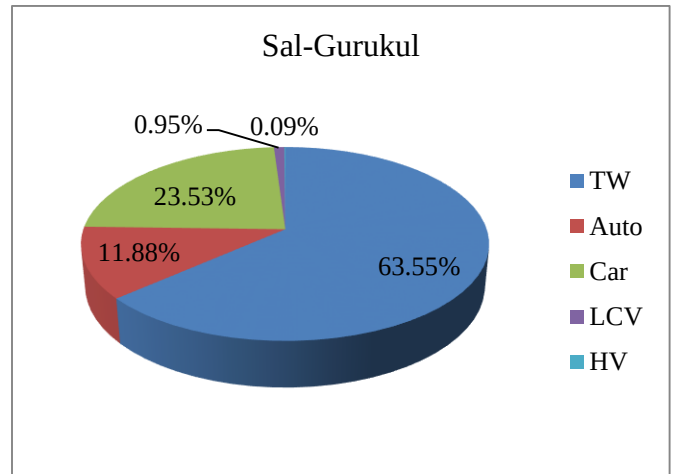
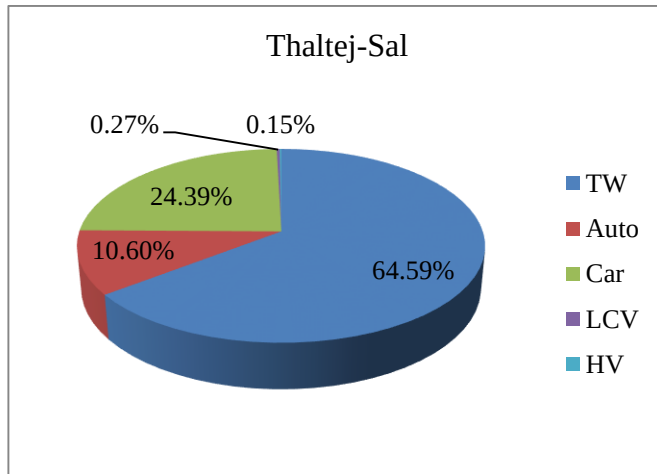


Fig. 9 Mean speed during construction

Data collection continued after the construction activities were completed. Data time of trip and volume of traffic have

been gathered. The vehicle proportion is displayed in Figure 10.



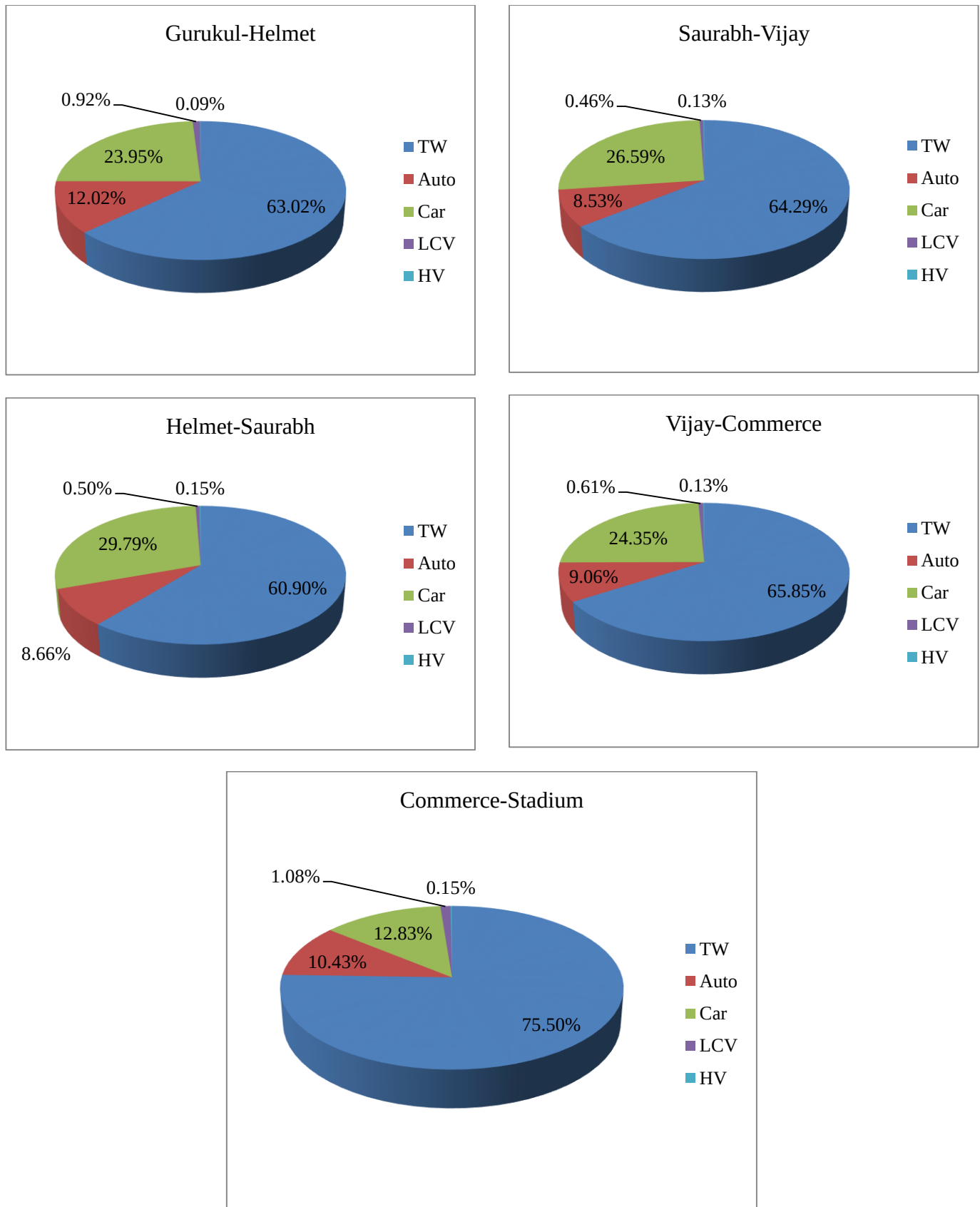
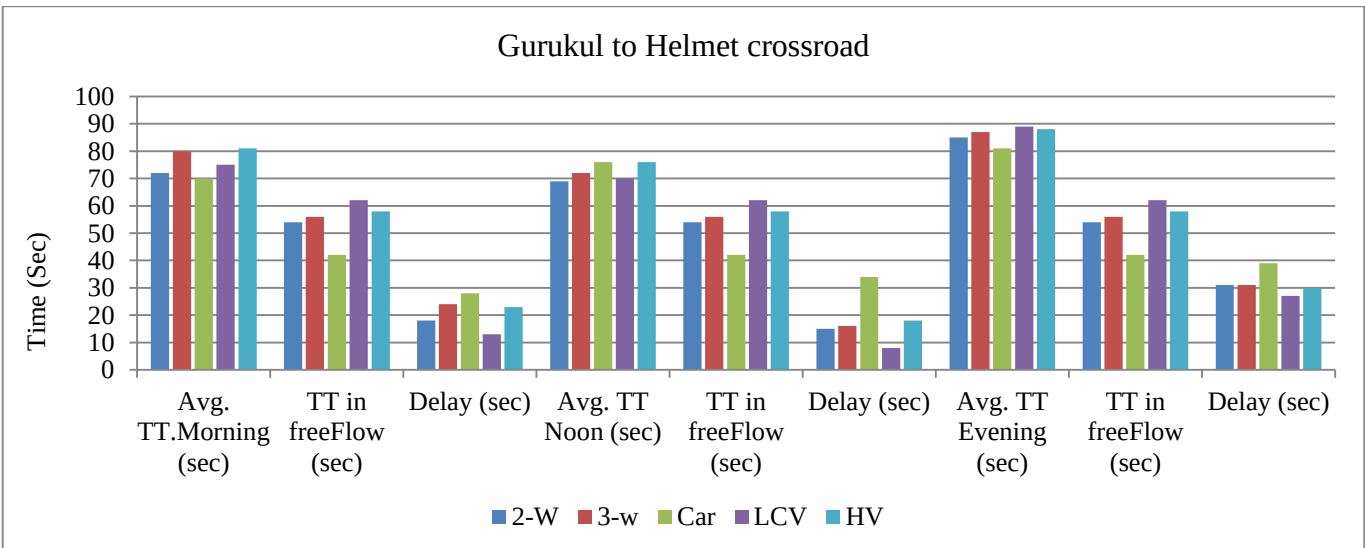
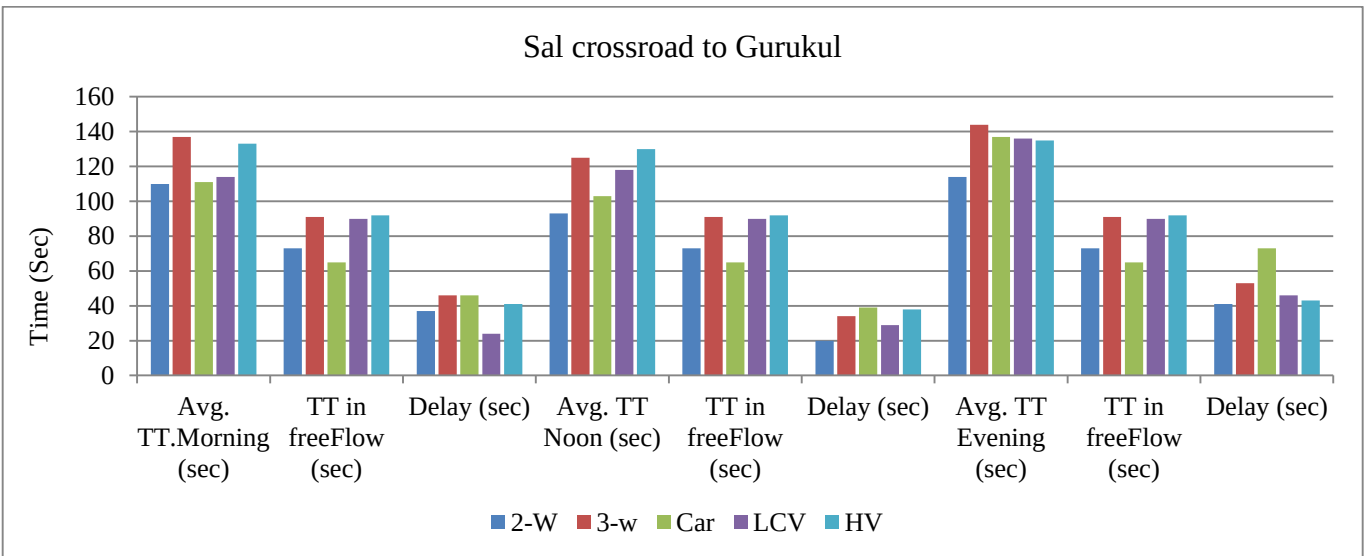
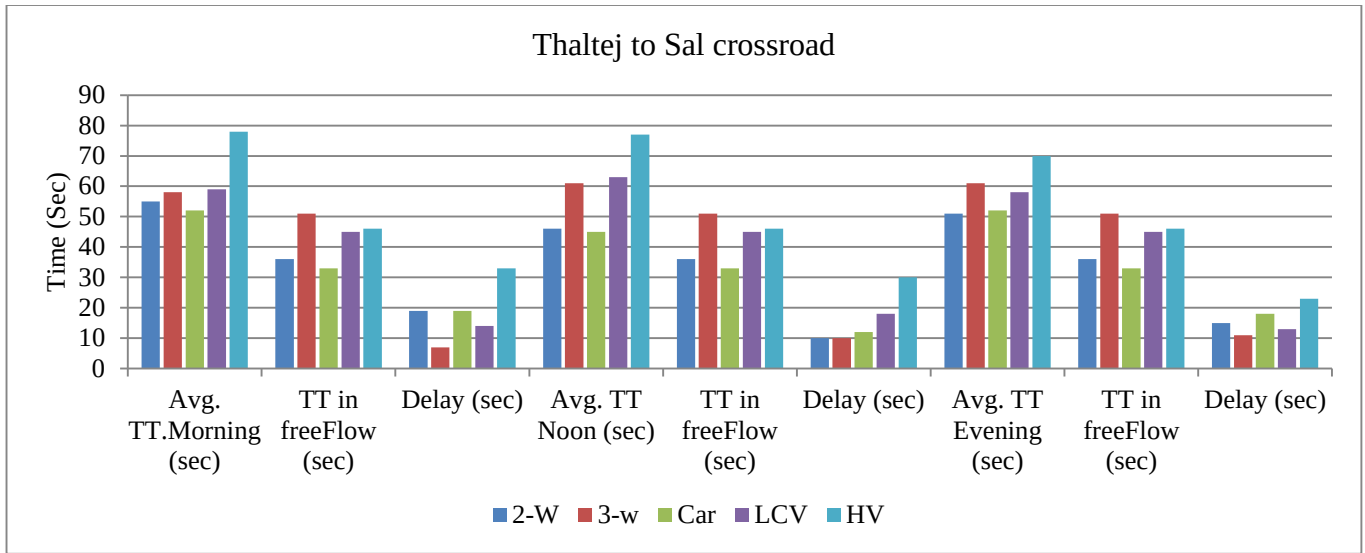
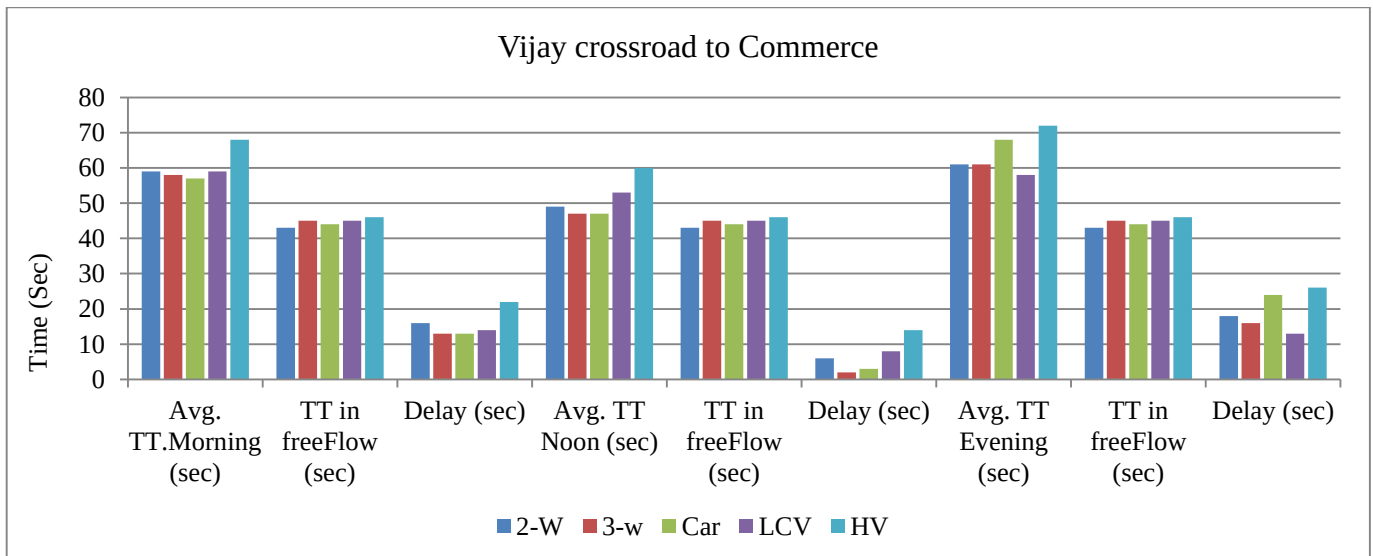
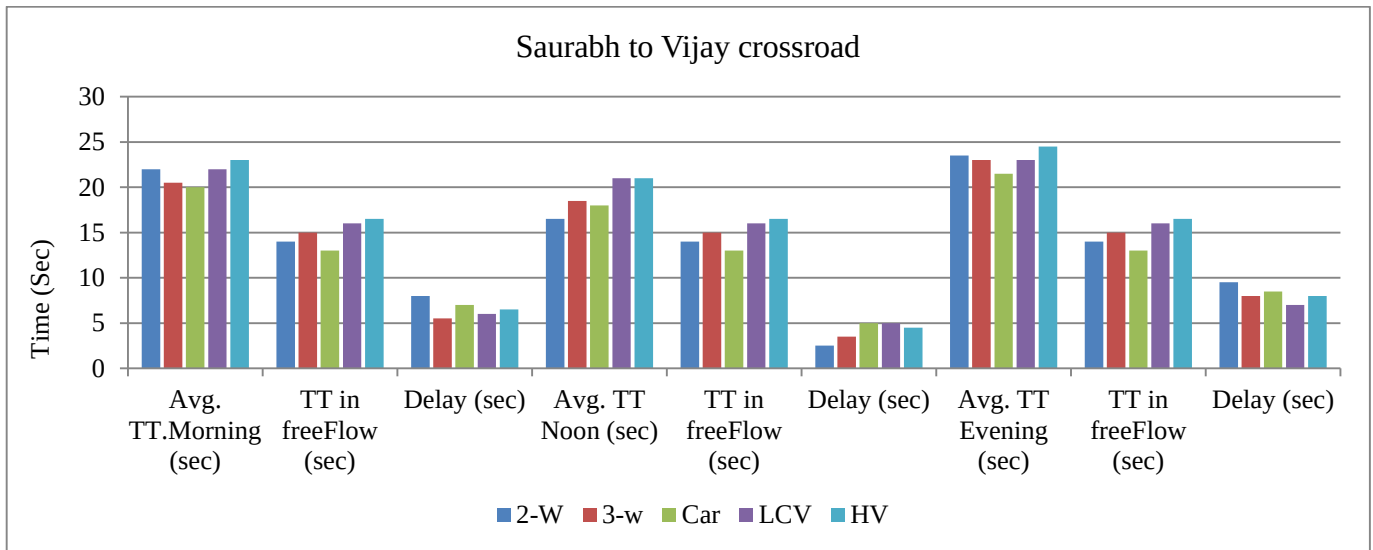
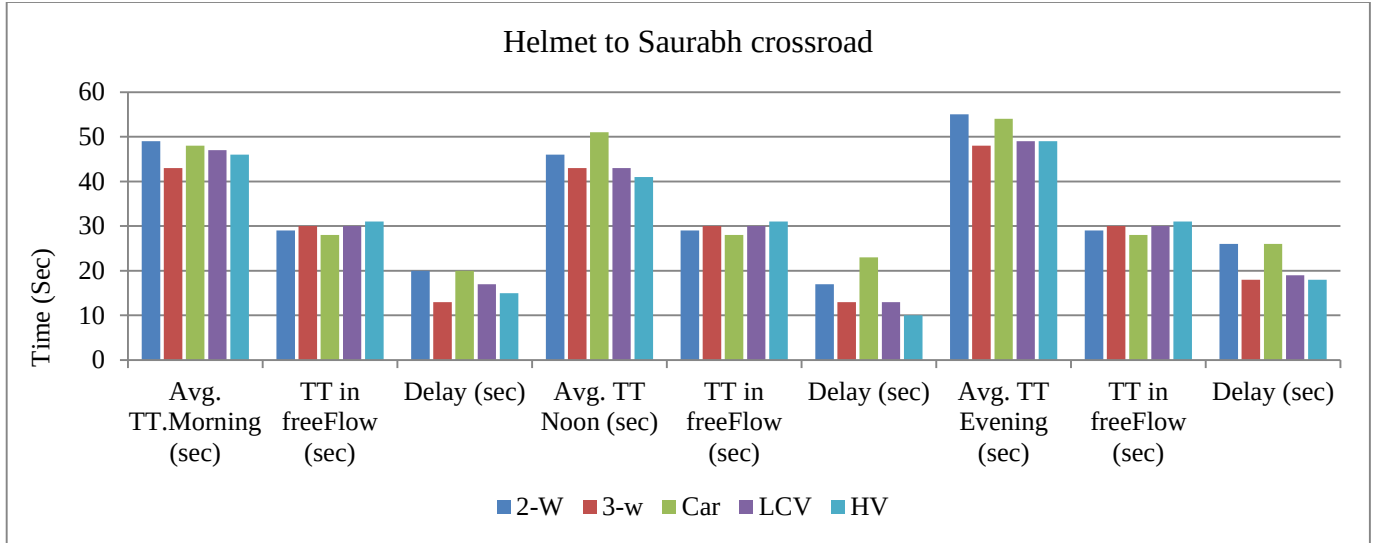


Fig. 10 Vehicle composition after completion of construction [27]





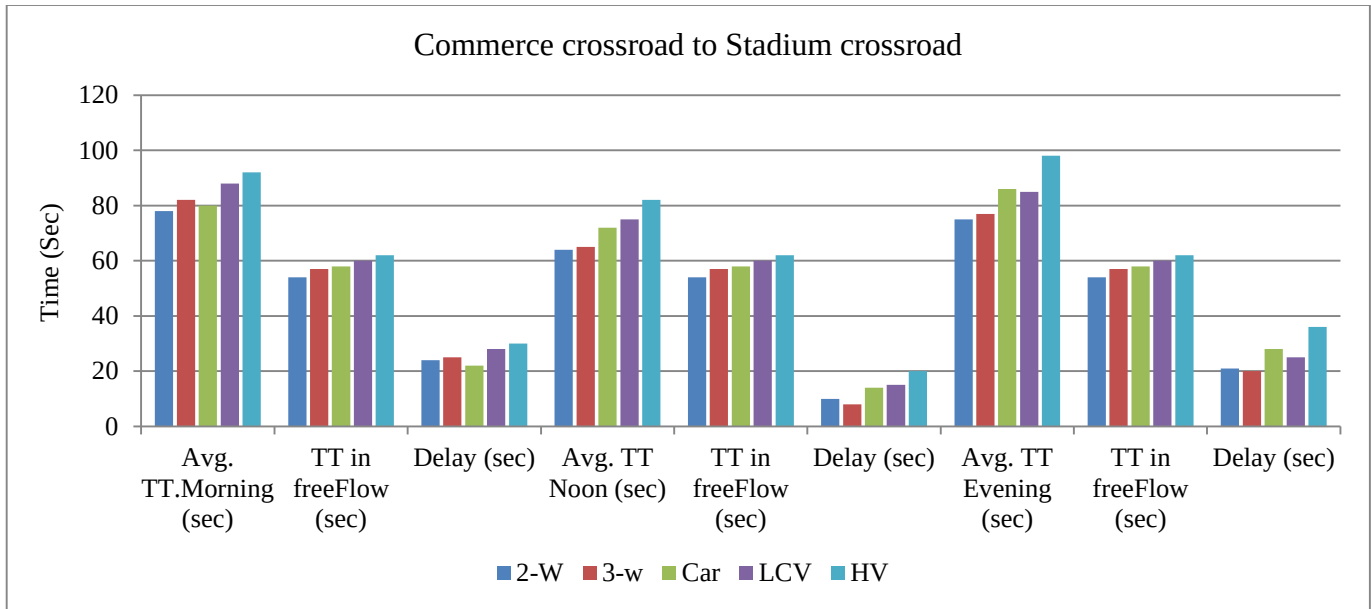


Fig. 11 Delay and time of travel time after completion of construction [27]

Figure 11 shows that the highest delay occurs in the evening and the lowest delay occurs during midday for all

links. Figure 12 depicts the average delay after completion of construction.

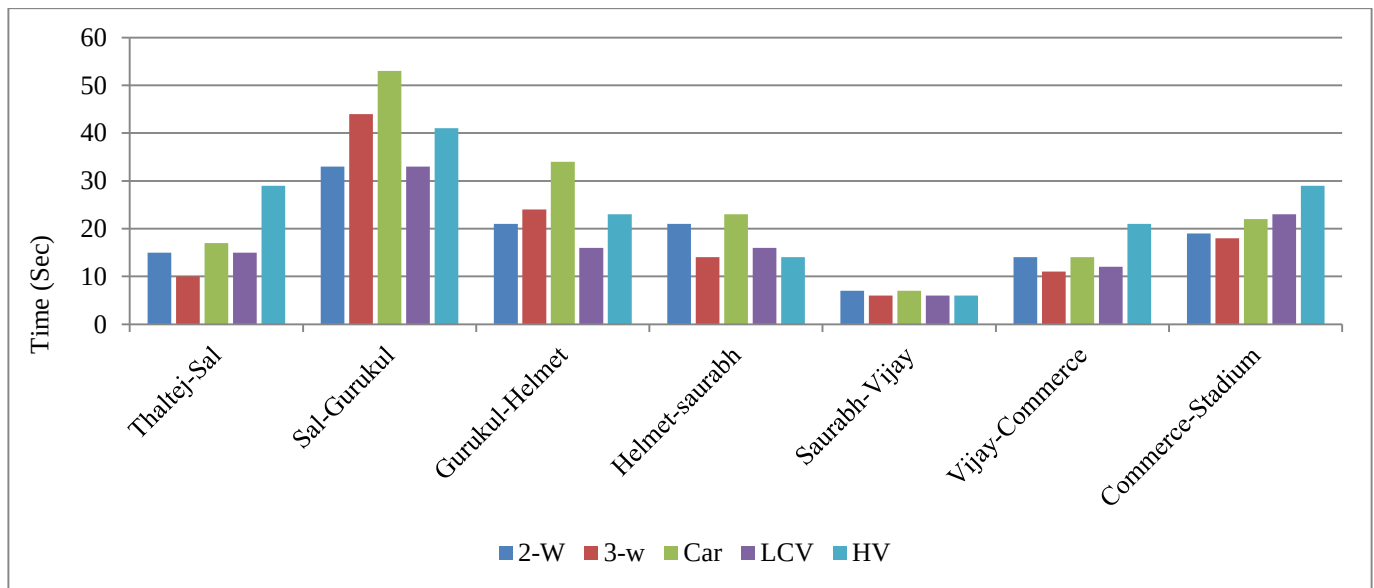


Fig. 12 Delay after completion of construction

Figure 12 shows that Link-2, extending from Sal to Gurukul, experiences the highest delay due to the predominance of commercial land use along the corridor. The connection of link-5, i.e., Saurabh to Vijay, exhibits the least amount of delay. Residential neighborhoods and abandoned government plots encircle this link. The linkages in this instance vary in length. Thus, speed may be a more useful metric to illustrate the effects of the building phase. Figure 13 indicates that Link-5, extending from Saurabh to Vijay, recorded the highest average speeds during morning, noon, and evening periods, with corresponding values of 34.7 km/h,

40.9 km/h, and 46.8 km/h, respectively. The link is characterized by surrounding residential areas, open spaces, and an available roadway width of 11.3 m. At the link of Gurukul to Helmet, the lowest speeds in morning, noon, and evening are recorded at 26.9 km/h, 28.1 km/h, and 22.7 km/h, respectively.

Despite the link's 12-meter carriageway width, the speed is lower. The link approaches the main intersection of the Navrangpura region and is encircled by a mall and two large hospitals.

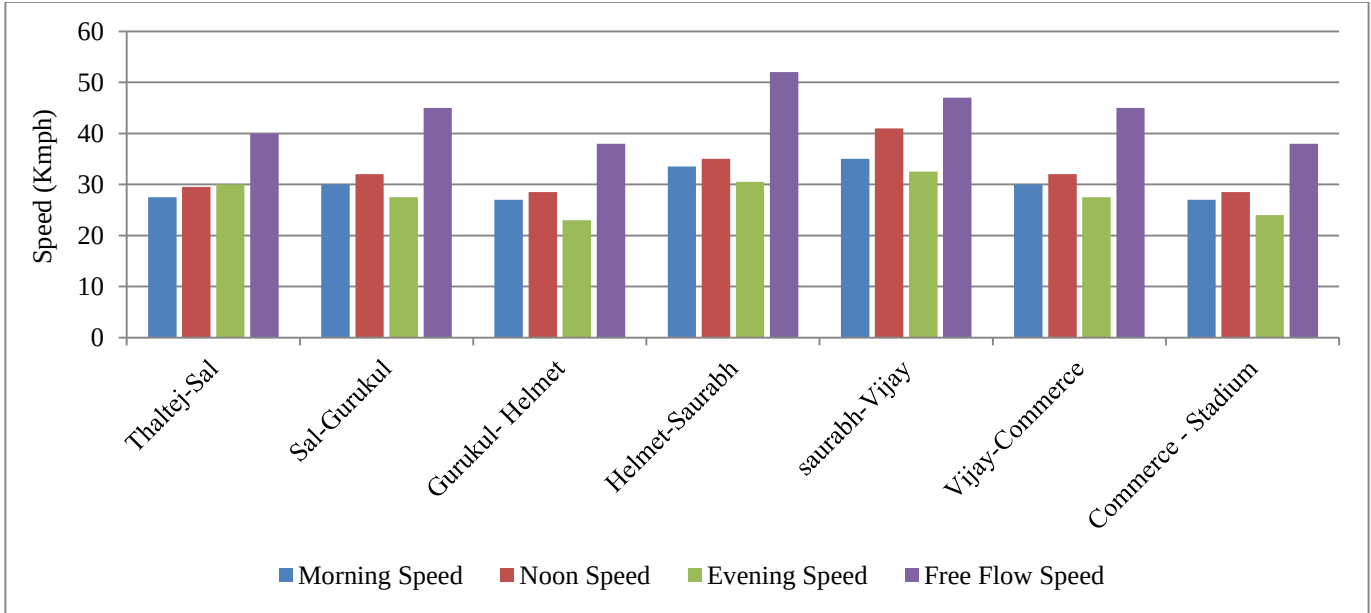


Fig. 13 Mean speed after completion of construction

6.5. Speed-Delay Relationship

Additionally, the connection between delay and speed has been inspected. Each link's mean delay and speed are considered. Figure 14 shows a graph of the delay-speed relationship during construction and after construction.

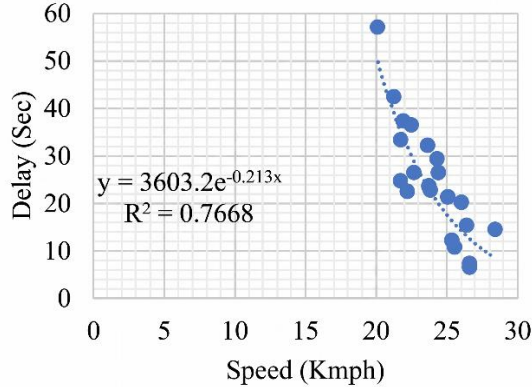


Fig. 14 Relationship between speed - delay during construction

During the construction phase, the graph displays an exponential relationship between delay and speed. Vehicle speed accounts for around 76% of the variation in delay, according to the coefficient of determination ($R^2 = 0.7639$), which shows a strong link between the variables. Delays are much greater at slower speeds, up to 50–60 seconds. Delays significantly decrease when speed increases from about 20 km/h to 28 km/h.

The dispersed points show variations in traffic circumstances brought on by lane limits, construction, traffic diversion, and disrupted traffic flow. Interpretation: Traffic flow gets erratic and crowded during the building phase.

Vehicles are forced to travel at slower speeds due to work-zone interference and reduced roadway capacity, which increases delays.

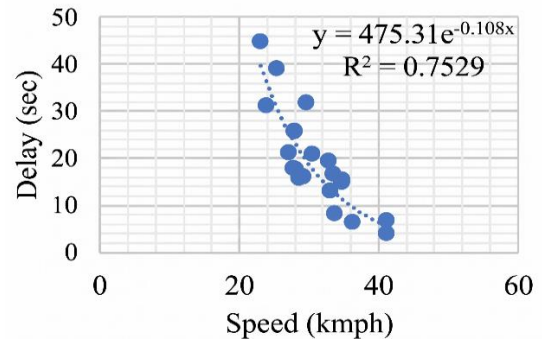


Fig. 15 Speed-Delay relationship (post construction phase)

The graph shows an exponential decline connection between delay and speed after construction. Additionally, a strong link is indicated by $R^2 = 0.7529$. As speed rises, delays quickly diminish.

While delays drop to less than 10 seconds, vehicle speeds considerably increase to about 40–42 km/h. In comparison to the construction-stage graph, the data points seem less dispersed and more constant, suggesting smoother flow of traffic.

Interpretation: After construction completion, roadway conditions improve, leading to smoother traffic flow, increased operating speeds, reduced interruptions, and lower vehicle delays. The exponential trend suggests that even moderate increases in speed can significantly reduce traffic delay after infrastructure improvement.

Figures 14 and 15 clearly demonstrate that construction activities negatively affect traffic performance by reducing vehicle speeds and increasing delays. During construction, traffic flow becomes unstable due to work-zone disruptions and restricted roadway capacity. After construction, speeds increase, and delays decrease considerably, indicating improved operational efficiency and smoother traffic movement.

Thus, the study confirms a strong inverse relationship amongst delay and speed and highlights the significant impact of construction activities on roadway performance. In this study, an overall delay comparison is done both during and post-construction phase. The research area's two-wheeler, three-wheeler, automobile, LCV, and HV delays during construction and after completion construction are compared in Figure 16.

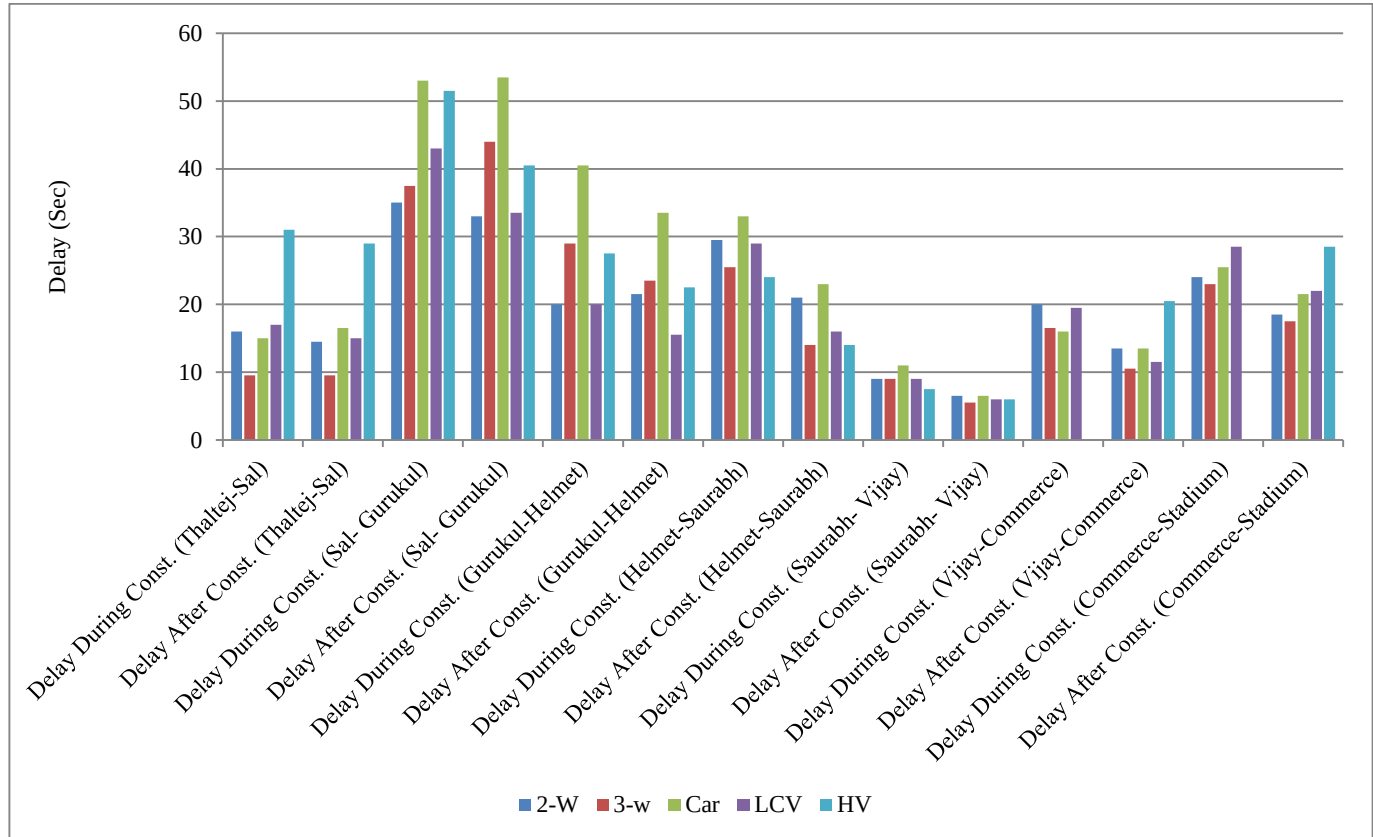


Fig. 16 Vehicle wise delay comparison

Table 4. Delay reduction following construction

Link No	Percentage decrease in delay				
	Two-Wheeler	Auto Rickshaw	Car	Light Commercial Vehicle	Heavy Vehicle
1	9.98	39.42	7.347	11.75	7.43
2	5.86	9.431	0.244	22.41	21.69
3	6.52	19.01	16.95	21.08	17.26
4	28.33	44.28	30.73	44.46	41.92
5	30	37.5	38.15	36	19.05
6	33.84	38.36	15.19	40	--
7	24.02	24.39	14.38	22.40	--

Figure 16 shows that after construction is completed, the travel delay decreases. Heavy trucks were not allowed to enter the linkages between Vijay to Commerce and Commerce to Stadium during construction. Because of this, HV is not there in the graph during the building phase. A decrease in delay has been noted for both the phases of construction, i.e. during and

post-construction study. The decrease in delay during post construction phase is displayed in Table 4. Table 4 shows that all the links' delays have decreased. Across all links and vehicle types, the reduction delay ranged from 0.244% for cars on Link 2 to 44.46% for LCV on Link 4.

7. Model Development

7.1. During Construction Stage Delay Prediction Model

A model for estimating delays during the project construction phase was developed. Several parameters, namely link length (m), Available Road Width (ALW) in meters, traffic flow (PCU/h), and average speed (km/h), were considered for model development. The descriptive statistics employed in the delay analysis appeared in Table 5, while the correlation matrix after the construction-stage delay analysis is provided in mentioned Table 6.

Table 5. Statistical summary of variables during construction

	Speed (S)	Length (L)	ALW	Flow (F)	Delay (D)
Avg.	27.28	367.18	5.22	1308.2	21.1
Std. error	0.72	9.85	0.05	18.20	0.48
Median	23.63	250.00	5.00	1226.5	12.36
Mode	20.69	1000.00	6.00	1419.0	17.03
Std. Dev.	19.21	262.80	1.47	485.71	12.69
Variance	369.1	69066.0	2.15	235914	160.9
Count	712	712	712	712	712

From Table 6, the independent factors such as ALW, Length (L) and traffic Flow (F) of traffic are showing better association with slowdown. Speed has medium relation with delay.

Table 8. Coefficients during construction delay model

Ind. Variables	Coeff.	Std. Error	t-stat	p-value	95% Confidence Interval	
					Lower bound	Upper bound
ALW	-1.027	0.17	-5.995	0.00	-1.363	-0.69
length	0.036	0.00	28.25	0.00	0.033	0.038
Flow	0.008	0.00	10.32	0.00	0.006	0.009
Speed	-0.137	0.02	-8.886	0.00	-0.168	-0.11

Table 8 shows that available ALW and speed are the main factors influencing delay, followed by flow and length, according to coefficient value. The variables' standard error values are low. Therefore, coefficients of variables can be predicted by this model more precisely.

The t-value represents the ratio between the regression coefficient and its corresponding standard error. In the present analysis, the t-values of all independent variables exceeded the critical t-value, suggesting that these variables notably affect traffic delays. Therefore, Available Lane Width (ALW), link length, traffic flow, and speed were identified as important explanatory variables affecting delay.

Table 6. Pearson Correlation among variables during construction

	Delay (D)	ALW	Length (L)	Speed (S)	Flow (F)
Delay (D)	1.000				
ALW	0.401	1.000			
Length (L)	0.844	0.440	1.000		
Speed (S)	-0.146	-0.226	-0.081	1.000	
Flow (F)	0.496	0.456	0.409	0.313	1.000

Delay = f (Available Lane Width (ALW), Flow (F), Speed (S), Length (L)). Table 7 shows statistics for regression.

Table 7. Regression summary during construction of delay model

Mult. R	R ²	Adjusted R ²	Std Error	Observations
0.951	0.904	0.901	6.09	461

Table 7 indicates an R² value of 0.904, suggests a strong correlation connecting the dependent and explanatory variables. Table 8 presents the coefficients obtained for the delay model through the construction stage. The interceptive value was fixed at zero since the independent variable is anticipated to vanish when all self-governing variable quantity are zero.

$$D = -1.02A - 0.137S + 0.036L + 0.00824F \quad (4)$$

Where, D = travel delay in sec, A = average lane width in meters, S = operating speed in km/h, L = work-zone length in meters, F = traffic flow in vehicles/hour or PCU/hour

7.2. Delay Model Validation (During Construction Stage)

ANOVA testing and cross-validation are the two techniques used to justify models.

ANOVA test for construction-stage delays is displayed in Table 9.

Table 9. Analysis of Variance (ANOVA) for delay (during construction)

	dof	Sum of Square	Meam Sum of square	F value	Sig. F
Regression	4	161057.1	40264.28	1084.018	2.5E-231
Residual	457	16974.61	37.14356		
Total	461	178031.7			

The regression yields an R^2 value of 0.9046. For a 95% CI, f critical value is 0.05. ANOVA yields positive results because f sig. is almost zero.

7.3. Cross Validation

Approximately 70% of the data were used for model development, whereas the left 30% were reserved for model validation. The link between the observed and estimated delay values is illustrated in Figure 17.

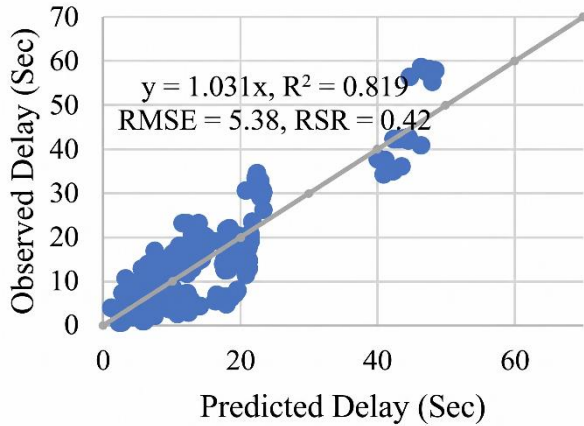


Fig. 17 Predicted vs observed delay

The comparison between observed and predicted delay values during the construction phase yielded an R^2 value of 0.819.

7.4. Delay Prediction Model (After Construction)

Available Lane Width (ALW), link length, car volume, auto-rickshaw volume, Light Commercial Vehicle (LCV) volume, Heavy Vehicle (HV) volume, traffic flow, and speed were considered as independent variables.

Table 10. Statistical summary of variables after construction

	ALW	Flow (F)	Delay (D)	Length (L)	Speed (S)
Mean	10.7	1351.1	14.83	571.2	31.70

Std. Error	0.08	21.9	0.54	10.34	0.222
Median	11.3	1470.6	19.7	565.0	30.71
Mode	11.5	1056.0	24.4	565.0	29.40
St. Dv.	1.56	474.2	11.6	223.4	4.80
No	467	467	467	467	467

The correlation results presented in Table 11 reveal that available road width demonstrates a relatively low association with delay, while independent variables, including length, speed, and traffic flow, exhibit stronger relationships with the supported variable. The regression statistics taken from the analysis are provided in Table 12.

Table 11. Pearson Correlation among variables after construction

	Delay (D)	ALW	Length (L)	Flow (F)	Speed (S)
Delay (D)	1.0000				
ALW	0.048	1.000			
Length (L)	0.804	-0.200	1.0000		
Flow (F)	0.221	0.725	-0.075	1.000	
Speed (S)	-0.632	-0.162	-0.318	-0.264	1.000

Table 12. Regression summary after construction of delay model

Multi. R	R^2	Adjusted R^2	Std. Error	Obs.
0.9785	0.958	0.954	4.972	292

As indicated in Table 12, the developed model achieved an R^2 value of 0.958, reflecting a strong correlation between observed and predicted values. For a 95% confidence interval, the adopted significance level was 0.05, confirming the adequacy of the model's performance. The estimated coefficients of the explanatory variables are summarized in Table 13.

Table 13. Coefficients of after construction delay model

Independent Variables	Coefficients	Std. Error	T stat	P value	Lower 95%	Upper 95%
Length (L)	0.042	0.00	36.78	0.00	0.04	0.045
Speed (S)	-0.413	0.02	-14.53	0.00	-0.47	-0.36
Flow (F)	0.007	0.00	13.08	0.00	0.01	0.01

According to Table 13's coefficient value, speed is the primary factor influencing delay, after that Flow (F) and Length (L) are affecting variables. The variables' std. error values are low.

The fraction of the measurement to its usual error is measured by the t-value. In this case, the independent

variables' t-values are greater than the t-critical value. Thus, they might be regarded as the causes that induce delay.

Additionally, the p-value is smaller than 0.05.

$$D = 0.042L - 0.413S + 0.007 \quad (5)$$

Where D = travel delay in sec, L = work-zone length in meters, S = operating speed, specify the unit, such as km/h
F = traffic flow vehicles/hour or PCU/hour

7.5. Delay Model Validation (After Construction Stage)

ANOVA testing and cross-validation are the two techniques used to validate models. ANOVA test for post construction stage is displayed in Table 14.

Table 14. Analysis of Variance (ANOVA) for delay (after construction)

	dof	Sum of Square	Mean Sum of square	F value	Sig. F
Regression	3	160592.1	53530.71	2165.279	3.5E-197
Residual	289	7144.751	24.72232		
Total	292	167736.9			

The regression model achieved a Coefficient of Determination (R^2) of 0.9574, reflecting a high degree of explanatory capability. Considering a 95% confidence interval with a significance level of 0.05, the ANOVA analysis demonstrated that the model was statistically significant, as the associated significance value approached zero.

7.6. Cross Validation

Approximately 70% of the data were used for model development, whereas the left 30% were reserved for model validation. The connection between the observed and estimated delay values is illustrated in Figure 18.

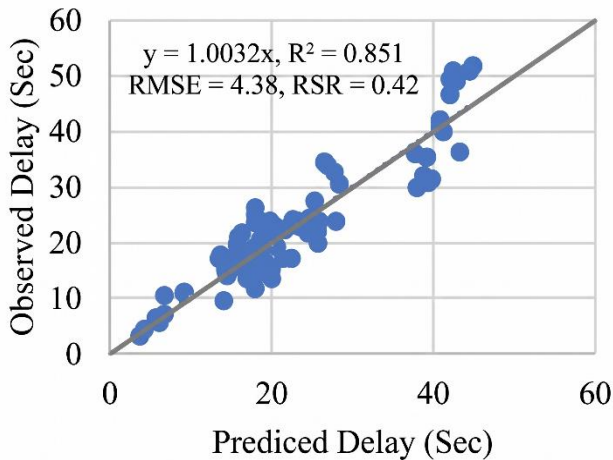


Fig. 18 Predicted vs observed delay after completion of Construction

The comparison between predicted and observed delays during the post-construction phase yielded an R^2 value of 0.851.

7.7. Impact of Work Zone Area on Delay

The data analysis gives an idea that there is a decrease in delays after completion of construction of work. Total limited area is computed from the length and width of work zone, which is displayed in Table 15, to study the impact of the construction work zone.

Table 15 indicates considerable alteration in the breadth of the study links. Figure 19 presents the distributed plot illustrating the relationship among restricted areas and interval differences.

Table 15. Work area

Sr. No.	Link No.	Width of work area (m)	Length of construction area (m)	Restricted area (m ²)
1	1	6.50	455.00	2957.50
2	2	6.00	1000.00	6000
3	3A 3B	8.70 6.50	205.00 445.00	1783.50 2,892.50
4	4A 4B	6.30 3.60	250.00 230.00	1575 828
5	5	6.00	215.00	1290
6	6A 6B 6C	4.00 5.60 6.70	397.00 76.00 107.00	1588 425.60 716.90
7	7	3.690	700.00	2583

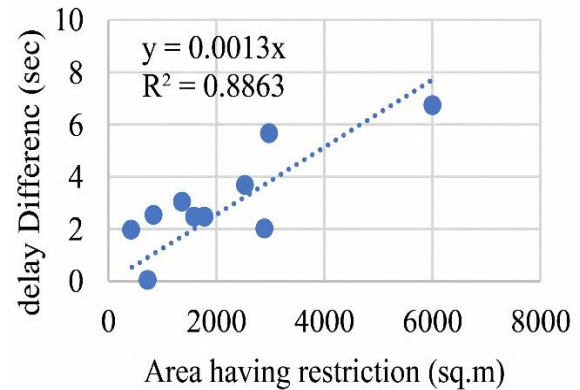


Fig. 19 Difference in delay vs restricted area

As illustrated in Figure 19, larger restricted areas within the work region relate to greater differences in delay. This highlights the substantial impact of work zones on traffic operations.

7.8. Testing of Hypothesis

It is used to obtain the observed results that are significant in hypothesis testing. It involves two theories that are mutually exclusive: Null Hypothesis (H_0): Following the construction phase (after work zone restrictions are lifted), there is no discernible change in delays. Alternative Hypothesis (H_a): Following the building phase, it is a notable shift in traffic delay.

$\bar{x}_a$ and $\bar{x}_b$ = mean values during and post construction phase, s_a and s_b = standard deviations, n_a and n_b = sample sizes

$$\sigma(\bar{x}_a - \bar{x}_b) = \sqrt{\frac{sa^2}{na} + \frac{sb^2}{nb}} \quad (6)$$

$$\sigma(\bar{x}_a - \bar{x}_b)Zc = 1.96 \times \sigma(\bar{x}_a - \bar{x}_b) \quad (7)$$

[29]

The H_a is accepted, and H_0 is rejected if the values found in calculation (7) are fewer than the performed deviation of mean (i.e., Monitored > critical).

Table 16. Delay hypothesis testing

Stat. Para.	Link-1	Link-2	Link-3	Link-4	Link-5	Link-6	Link-7
$\bar{x}_a$ (Sec)	17.03	46.22	28.6	27.99	9.654	24.4	26.48
$\bar{x}_b$ (Sec)	5.75	41.55	23.76	20.36	6.644	15.34	22.64
S_a (Sec)	3.5	8.638	6.73	5.286	2.91	3.623	7.353
S_b (Sec)	1.35	9.488	6.29	3.623	3.23	6.492	6.7
n_a	65	66	65	64	65	66	66
n_b	64	65	65	64	65	66	65
$\sigma(\bar{x}_a - \bar{x}_b)$ at 95% confi. interval (Sec)	0.92	3.1	2.23	1.6	1.0	1.82	2.43
difference of mean (Sec)	11.28	4.67	4.84	7.63	3.01	9.06	3.84
Result: The observed result is above the critical level. So, (H_0) null hypothesis was rejected in favor of the (H_a) alternative hypothesis.							

8. Conclusion

8.1. During Construction Stage Delay Analysis

- The range of 2W percentages is 55% to 79.7%. The percentage of cars ranges from 7.7% to 15.6%. The percentage of autos is 7.3% to 32%. At 26.07 km/h, the link-1, i.e., Thaltej to Sal, has the fastest speed. The link's road width was consistently 6.0 meters. The Gandhinagar-Sarkhej highway is linked to this segment. There is vacant space all around this segment. With the speed of 22.42 km/h, the link-4, i.e., Helmet to Saurabh, has the lowest speed. The Helmet intersection is a significant intersection that links two important roadways, which is the primary cause. A BRTS corridor is at this intersection as well. Because of construction activity of the metro station, traffic was moving slowly as soon as you left the Helmet junction.
- The length of the links varies. Thus, the delay per kilometer has been computed. Link-4, i.e., Helmet to Saurabh route, has the large delay, at 58.68 seconds per kilometer per vehicle. Heavy traffic leaving the Helmet intersection is the primary reason for the delay. Link-6, i.e., Vijay to Commerce, has the lowest delay, at 31.53 seconds per kilometer per vehicle. Residential areas partially encircle the link. Hence, links have a less proportion of slow-moving vehicles.
- A negative exponential association exists between vehicle speed and traffic delay.
- Link length, Available Lane Width (ALW), traffic flow, and speed are the major factors governing delays during the construction stage.

8.2. After Construction Stage Delay Analysis

- The 2W percentage is 57.29% to 77.29%. Auto percentage is 7.65% to 15.6%. The percentage of cars is 10.42% to 33.45%.

- The fastest speed is 41.02 km/h at link-5, i.e., Saurabh to Vijay, while the slowest speed is 23.76 km/h at link-3, i.e., Gurukul to Helmet. There are numerous hospitals, stores, shopping centers, and temples all around this link.
- The length of the links varies. Thus, delay per km was computed. Link-3 i.e., Gurukul to Helmet, is having the longest delay, measuring 55.51 seconds per kilometer per hour. Link-6, i.e., Vijay to Commerce, has the lesser delay, at 11.30 seconds per kilometer per vehicle. Speed-delay have a negatively exponential connection.
- Length, flow and speed are factors that impact post-construction delays.
- Findings from the literature reveal that speed, lane closure type, and the proportion of heavy vehicles are among the key variables affecting delay estimation. Several analytical and modeling approaches, including multilinear regression, simulation-based methods, and artificial neural networks, have been widely adopted for delay prediction and analysis.

9. Discussion

The comparatively improved model performance may be attributed to the inclusion of work-zone-specific variables and the use of field data collected under actual operating conditions. Unlike many previous studies that primarily considered traffic flow and roadway characteristics, the present study incorporates available lane width and construction-related restrictions affecting traffic operations. Furthermore, the model was developed and validated using observed field data from both construction and post-construction conditions, enabling a more detailed representation of delay variation. However, the results remain dependent on the characteristics of the study corridor, and further validation on other corridors is required to establish broader applicability.

9.1. Comparison of Existing Conclusions with Prevailing Information

Prior studies were principally focused on freeway work areas, simulation-based analyses, or traffic conditions characterized by homogeneous vehicle composition. In comparison, the present investigation examined real-world heterogeneous urban traffic conditions during metro rail construction activities in Ahmedabad city. Empirical postponement assessment models were acquired using field data accumulated for both construction-stage and post-construction scenarios. The findings reveal that work zone restrictions substantially increase travel delay, especially along urban arterial corridors carrying mixed traffic streams.

9.2. The Novelty of the Present Study Lies in

- The evaluation of travel delay under mixed traffic conditions involving two-wheelers, auto-rickshaws, cars, and commercial vehicles.
- Comparison of traffic analysis conducted before and after metro rail construction.
- Development of field-based practical delay prediction models using actual traffic data.
- Consideration of urban factors such as barricading, lane width reduction, and varying road conditions.
- Analysis of the restricted work area impact on travel delay.
- These findings provide useful, relevant information for planning and managing the long-term urban infrastructure work zones under mixed traffic conditions.

9.3. Limitations

The analysis is limited to one study corridor and two survey phases. While the corridor characteristics and traffic control conditions remained largely unchanged, variations in traffic demand and driver behavior may have influenced the

results. In addition, the developed delay model was tested only on data from the study area; therefore, further validation using data from different corridors and work-zone conditions is recommended before broader application.

9.4. Suggestion and Recommendations

In view of the assumptions drawn from the study, several measures are proposed to reduce the negative impacts of construction work in urban regions.

- Optimize signal timings and manage road capacity during the closing of lanes due to construction.
- Use ITS and traffic monitoring to control congestion effectively.
- Conduct assessment of impact of traffic before starting construction activities.
- Provide timely information regarding construction schedules, diversions, and mitigation measures to the public.
- Prepare comprehensive plan of traffic management in coordination with stakeholders and concerned authorities
- To reduce traffic and travel delays, provide and notify drivers about the alternative routes and modes of transportation.
- Install proper signage and ensure effective communication to inform road users about construction activities and traffic diversions.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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