

Evaluation of Lane-Based Traffic Segregation and Access Spacing Strategies under Heterogeneous Urban Traffic Conditions

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ABSTRACT

The heterogeneous traffic conditions commonly observed on arterial corridors in developing countries, such as India, present considerable challenges to traffic efficiency, safety, and environmental sustainability. These challenges arise from the presence of diverse vehicle types, irregular lane discipline, and uncontrolled access points. The objective of this research article is to understand the role of lane segregation and separation of access points in enhancing traffic operations in developing countries with these types of traffic conditions. To gather the necessary information for an evaluation of how lane segregation and access point separation will enhance traffic operations, the Fatima Nagar-Hadapsar Gadital corridor located in Pune was selected for extensive field collection of traffic volume data, vehicle classification data, and lane utilisation data. Using the collected data, a market-consumer traffic simulation model was created using VISSIM to duplicate the behaviour of traffic operating under noisy and unreliable conditions. The simulation simulated various combinations of different types of lane segregation strategies as well as combinations of different access point separation intervals. The key performance indicators analysed were average speed, average travel time, delays, queue lengths, levels of service and conflict points (as surrogates for safety). The combination of these strategies produces an increase in the level of service (the degree of service) of the roadway and a corresponding decrease in the detrimental impact of traffic congestion on the environment. This research also presents opportunities for providers to improve urban mobility and road design and develop relevant policies.

Keywords:- Heterogeneous Traffic; Lane Segregation; Access Management; VISSIM Simulation; Level of Service (LOS).

1. INTRODUCTION

India has the second-largest road network in the world, with a total of around 4.6 million kilometres. The large increase in the number of vehicles using these roads requires a more efficient system for the transportation of goods and people across the country. Traffic in India is expected to increase in the coming years in line with the fast pace of social and economic growth. Recognizing this, the Government of India (GOI) has introduced new initiatives under the National Highway Development Program (NHDP) to develop high-density corridors, such as multilane highways and expressways, to address the present and future needs for a fast, efficient, safe, and well-connected highway system. The use of multilane highways demands careful attention to traffic flow and capacity. Lane-changing and overtaking movements are common on these highways, some of which are involved in serious accidents. Therefore, it is necessary to identify the properties of lane-segregated traffic flow and lane-changing vehicle behavior. Many researchers have focused on vehicle behaviors related to lane-changing, as well as parameters such as average speed, travel time, delay, queue length, level of service, and conflict points. Other studies have examined the macroscopic properties of lane-changing traffic, such as the transfer of flows between lanes. [1-3].

As per traffic congestion Pune ranked number 4th most congested city globally [Source: TOMTOM] According to records provided by the Regional Transport Office (RTO), between 2001 and March 2024, a total of 3,684,964 vehicles were registered in Pune, including 2,563,987 two-wheelers, 1,007,243 four-wheelers, and 113,734 auto-rickshaws, of which 80,825 were electric vehicles. This corresponds to an average of 153,540 new vehicles per year. The rapid growth in vehicles has contributed to traffic congestion, accidents, parking issues, and various forms of pollution

The Fatima Nagar-Hadapsar Gadital corridor in Pune, part of the larger Solapur Road stretch, is a key arterial route experiencing significant development, featuring remnants of a planned Bus Rapid Transit System (BRTS), ongoing road widening, and planned Pune Metro Phase-2 connectivity, though commuters face issues like

congestion and mixed traffic, with ongoing infrastructure work like new arms at Gadital improving local connectivity to IT hubs like Magarpatta and Eon IT Park. [Source: Wikipedia].

This paper investigates lane segregation in traffic, which is the allocation of specific lanes to particular categories of vehicles, and access-spacing measures, which are rules that regulate the entry of vehicles into the road from driveways and side roads. The paper also investigates how these measures affect travel time, mean speed, queue formation, delay, and level of service, as well as safety measures such as time to collision and post-encroachment time. Traffic surveys and road inventory data are used to validate a microscopic simulation model of VISSIM, which is capable of simulating various lane segregation and access measures in a real-world setting. The following sections will review existing research, explain our methods in detail, present our simulation and validation results, discuss what these findings mean, and conclude with recommendations for managing urban traffic in rapidly developing cities.

2. LITERATURE REVIEW

Das and Chilukuri (2024) proposed two mathematical models for multi-class vehicle segregation to reduce total system travel time and crash risk in heterogeneous urban networks. The results obtained from the real-world mixed-traffic network showed a 10% reduction in travel time compared to the traditional traffic assignment model. The heuristic method proposed in the study ensured an optimal balance between efficiency and safety, thereby proving that lane segregation based on vehicle type can improve traffic flow.

Madhu, Srinivasan, and Sivananda (2024) investigated vehicle-following maneuvers in heterogeneous traffic conditions, emphasizing the influence of lane position and the presence of neighbouring vehicles. Based on trajectory information, they developed longitudinal acceleration models that consider the properties of surrounding vehicles. The findings showed that ignoring lane position and dynamics of neighbouring vehicles leads to large prediction errors, thus emphasizing the need for microscopic traffic models that accurately capture mixed-traffic interactions to improve simulation accuracy.

Trivedi and Gor (2017) enunciate key findings on the importance of lane discipline in maintaining optimal and safe traffic flow. The study shows that lane discipline is a factor in the reduction of delays and the preservation of speed, density, and lateral movements. On the other hand, the lack of lane discipline, which is common in Indian mixed traffic conditions, causes inefficiencies and increases the potential for crashes. The authors argue that traffic management practices must move beyond the construction of lanes to incorporate behavioral aspects, making lane discipline the key factor in safe urban mobility.

Chawla and Khare (2024) proved the relevance of microscopic simulation models, like VISSIM, to represent the complex phenomena of mixed traffic on Indian roads. By properly calibrating the simulation model using sensitivity analysis and ANOVA, the authors were able to identify key parameters that affect the performance of heterogeneous traffic. The above discussion highlights the importance of adapting simulation models to local traffic conditions to enhance accuracy and provide evidence-based solutions for lane segregation on Indian roads.

Srikanth et al. (2020) examined lane-changing maneuvers on multilane roads in non-lane-disciplined traffic conditions using a VISSIM simulation with a heterogeneous traffic pattern calibration. The results show that higher discretionary lane-changing maneuvers decrease overall speed and capacity. The paper concludes that simulation models need to incorporate erratic lane choice maneuvers to accurately assess multilane road performance in mixed traffic conditions.

Kotagi et al. (2020) explored vehicle placement and subsequent movement under heterogeneous traffic flow conditions on India's non-divided urban road system. Their results show that without lanes to properly segregate vehicles from each, there is greater lateral interaction between vehicles, which contributes to a decrease in overall capacity and, ultimately, to the establishment of flow characteristics that are similar to the issues you are attempting to address at your study intersection since lane-based behaviour is so vital.

J. Athira, K. N. Athulya, Y. V. Navandar, and K. Karuppanagounder (2026) took a close look at how side-road access traffic shapes the way drivers behave at signalized intersections, especially where the traffic is mixed and lane discipline is weak. They noticed that when vehicles merge in from side roads, it creates a lot of side-to-side conflicts. Drivers end up changing speeds, hesitating, and stopping and starting more as they approach the intersection. Even with just a moderate amount of traffic coming in from access points, the delays and congestion get noticeably worse. Their findings bring some much-needed clarity to how these intersections work and offer real value to anyone studying access spacing or lane segregation in Indian city traffic.

A study conducted by **Taware and Nadar (2019)** found that enabling motorized vehicles to use BRT (Bus Rapid Transit) lanes for a distance of 50 meters before an intersection would improve throughput, reduce queue times and increase speed while not compromising the operating performance of the BRT system. However, the authors also warned of possible short-term safety concerns as well as a slight rise in emissions levels.

In a similar study by **Sharma and Swami (2012)**, terminating the BRT-only lanes before the intersections was found to greatly reduce delays and emissions as well as to significantly enhance overall traffic performance. Both studies indicate that a hybrid lane approach, which provides for a balance between dedicated bus lanes and mixed-traffic lane flow, is the most effective means of achieving an efficient traffic intersection in a mixed-use transit system.

3. STUDY AREA

The study was conducted at Magarpatta Hospital Junction, (Fatima Nagar-Hadapsar Gadital corridor) a signalized intersection in the fast-growing Hadapsar, Magarpatta area of Pune City, India. This location is known for heavy evening traffic and a mix of different vehicle types. The junction connects Magarpatta City IT Hub, Amanora Township, and businesses along Solapur Road. Traffic here is diverse, with no strict lane discipline. Many two-wheelers make up 30 to 45% of the traffic, along with autos, cars, and delivery vehicles. Buses stopping, commercial loading and unloading, and nearby driveways often add to the congestion. Vehicle movement is unpredictable due to irregular lane use and frequent side-to-side movement.

The intersection has three arms, each with different road widths and mixed uses. Signal cycles last about 150 seconds, and green times change based on traffic demand. This location is on the Hadapsar-Solapur Road corridor, handling traffic between Kharadi-Magarpatta Road, Pune-Solapur Highway, and Amanora Park Town.

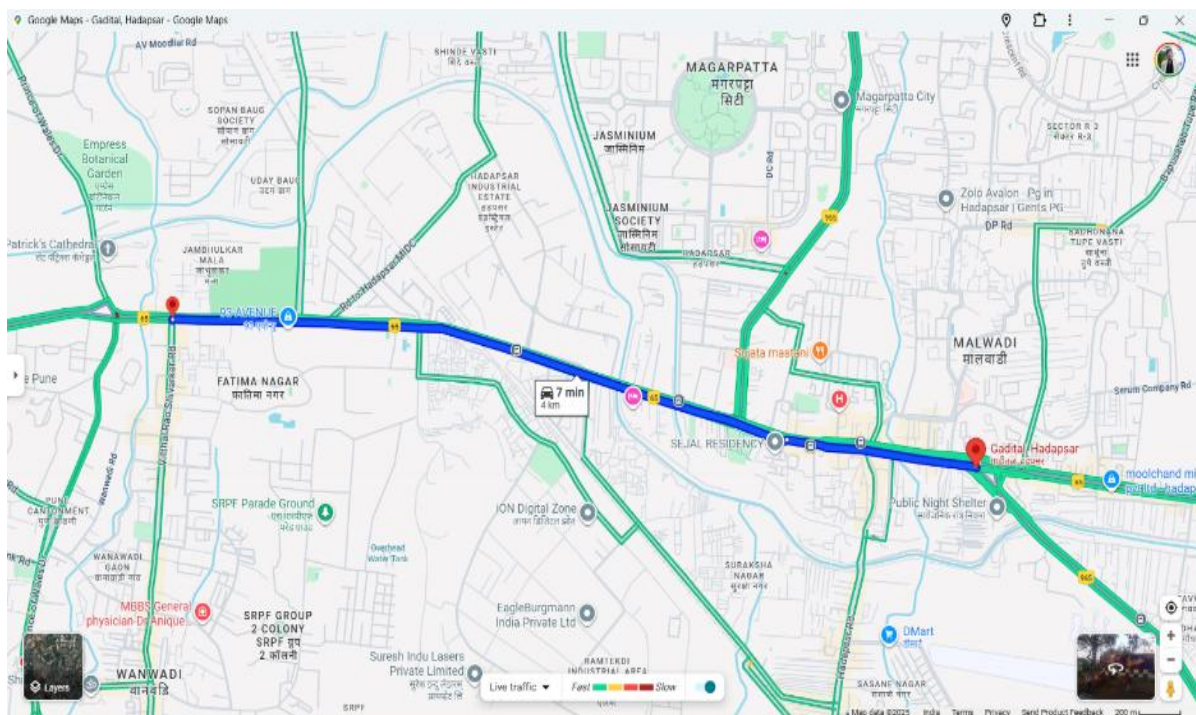


Figure 1 Aerial view of data collection Location (Fatima Nagar - Hadapsar Chowk), Pune

4. FIELD DATA COLLECTION

Field data collection during evening peak hours (17:30–19:30) combined video-based traffic recording with direct field observations. This approach allowed for the capture of comprehensive traffic parameters, including vehicle classification, flow rates, queue lengths, and discharge characteristics, essential for understanding complex traffic dynamics at the intersection.

4.1 Video-Based Traffic Recording

High-definition video cameras were positioned at elevated and unobstructed vantage points. Full-cycle signal operations were recorded during peak hours. Video data provided inputs for

- Approach-wise vehicle arrivals
- Classified volume counts (six categories: two-wheelers, three-wheelers, cars, light commercial vehicles, buses, trucks)
- Queue formation and dissipation patterns
- Cycle length and green time
- Discharge rate and saturation flow



Figure 2 Data Collection Location

4.2 Field Observations

Manual field observations were conducted at the Hadapsar flyover intersection, supplementing video-based data collection by documenting nuanced behaviours that are difficult to capture digitally. Direct on-site observations recorded

- Stop-line compliance and encroachment
- Queue formation and spillback
- Lane discipline and lateral movement patterns
- Influence of roadside activities
- Pedestrian interference
- Turning movement conflicts

These ground insights were essential for understanding the mixed traffic realities of the site. Lane-less movements, a mix of different vehicles, and roadside friction greatly affect intersection performance. By combining physical observation with video recording, we gained a more accurate input for microsimulation. This approach reflects actual driver behavior instead of depending only on traffic counts.

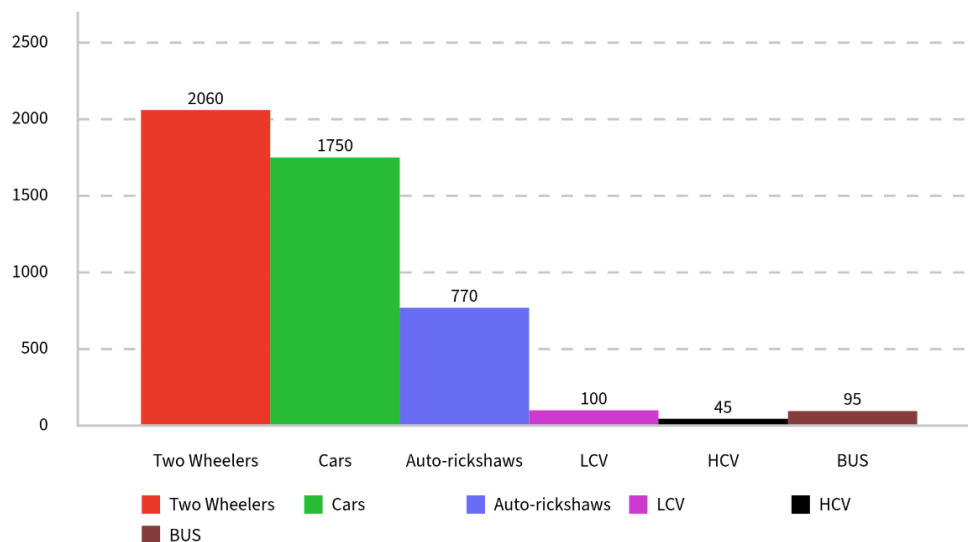


Figure 3 Composition of vehicle types signalized intersection approach

5. DATA ANALYSIS AND PERFORMANCE EVALUATION

Videos were analysed frame by frame using manual extraction software. This defined the maximum longitudinal space taken up by stopped or slow-moving vehicles (less than 5 km/h) upstream of the stop line. We measured queue lengths in meters and vehicles, averaging over cycles. Vehicles were classified into six categories: two-wheelers, three-wheelers, cars, light commercial vehicles, buses, and trucks, as shown in Fig 3. We calculated saturation flow from discharge rates after the green startup, noting the number of vehicles discharged every 5

seconds. PCU factors were derived from tests, adjusting for road width, composition, and indiscipline for each arm. Fig 4.



Figure 4 Magarpatta Chowk Intersection

5.1 Data Processing and Queue Estimation

The performance assessment of the Hadapsar flyover intersection used analytical methods that followed the HCM (2016) and Indo-HCM frameworks for mixed signalized traffic. Turning movement volumes collected from field video were converted into PCU using standard equivalency factors and combined to determine hourly demand at the approach level. Saturation flows were calculated using Indo-HCM geometric and performance adjustment factors, which accounted for lane width, lateral friction, and non-lane behavior. Manual evaluation provided capacity, degree of saturation, queue estimates, control delay, and LOS for each movement. This created a clear reference baseline before calibrating the microsimulation.

5.2 Saturation Flow Formula

Saturation flow represents the maximum discharge rate of a traffic stream through an intersection approach under ideal conditions, expressed in PCU per hour per lane.

$$S = s_0 \times N \times f_w \times f_{HV} \times f_g$$

Where:

- S = Adjusted saturation flow (PCU/hr/lane)
- s_0 = Base saturation flow (PCU/hr/lane)
- Typical urban India assumption (IRC/HCM practice):
 $s_0 = 1800$ PCU/hr/lane
- f_i = Adjustment factors for prevailing conditions such as:
 - Lane width factor f_w
 - Heavy vehicle factor f_H
 - Gradient factor f_g

5.3 Flow Ratio

Flow Ratio for each approach was estimated using the HCM deterministic Flow Ratio. This is suitable for undersaturated operating conditions.

$$y_i = \frac{q_i}{s_i}$$

Where:

- q_i = PCU demand (PCU/hr)
- s_i = Saturation flow (PCU/hr)

5.4 Optimum Cycle Length (Webster)

For the study intersection, Webster's method could not be used because of oversaturated conditions ($\sum y_i > 1$).

$$C = 140 \text{ s}$$

As a result, a practical signal cycle length of 140 seconds was chosen based on IRC practice for congested urban intersections. The effective green time was estimated at 128 seconds, accounting for a total lost time of 12 seconds per cycle. Using the chosen cycle length and effective green time, we calculated the volume-to-capacity (V/C) ratios for individual movements. We then verified the computed V/C ratios, and they were found to be consistent with the estimated saturation flows and movement capacities.

5.5 Green Time Allocation

The effective green time was divided among the signal phases based on the corresponding critical flow ratios, following this relationship:

$$g_i = \frac{y_i}{\sum y} \times G$$

Using this method, the total effective green time of 128 seconds was distributed across the three signal phases. The major through movement (Phase 1) got 52 seconds, the major right-turn movement (Phase 2) received 40 seconds, and the minor road movement (Phase 3) was allocated 36 seconds of green time. The sum of the allocated green times equals the available effective green duration and aligns with the estimated flow ratios and chosen signal cycle parameters.

5.6 Capacity and V/C Ratio Estimation

The capacity of each signal phase was estimated by using the saturation flow relationship.

$$c = s \times \left(\frac{g}{C} \right)$$

where:

- c = approach capacity (veh/h or PCU/h),
- s = saturation flow rate (veh/h or PCU/h),
- g = effective green time for the movement (s),
- C = cycle length (s).

Using the adopted signal timing parameters, the capacities for Phase 1 (Major Arm-1), Phase 2 (Major Arm-2), and Phase 3 (Minor Arm) were estimated at 1581 PCU/hr, 1581 PCU/hr, and 591 PCU/hr, respectively. The corresponding volume-to-capacity (v/c) ratios were calculated as 1.37 for Phase 1, 1.37 for Phase 2, and 1.39 for Phase 3. These results show that all phases operate under oversaturated conditions during the evening peak hour. The computed v/c ratios were checked and found to be consistent with the estimated saturation flows, allocated green times, and observed traffic demand.

5.7 Queue Length Estimation and Control Delay Estimation

Based on the chosen signal timing parameters and the estimated degrees of saturation, we evaluated analytical control delays using HCM-based delay formulas. The estimated control delays for Phase 1 (Major Arm-1) and Phase 2 (Major Arm-2) range from 95 to 110 s/veh. Phase 3 (Minor Arm) experiences slightly higher delays, ranging from 100 to 115 s/veh. The average intersection delay was estimated to be around 105 to 110 s/veh, which corresponds to Level of Service (LOS) F for all signal phases during the evening peak hour.

In addition, 95th-percentile queue lengths were estimated to evaluate queue formation under oversaturated conditions. The major road approaches (Phases 1 and 2) show queue lengths between 45 and 55 PCU, which is about 110 to 140 meters. The minor road approach (Phase 3) has queue lengths of 35 to 45 PCU, or roughly 95 to 120 meters. These delay and queue estimates match the high volume-to-capacity ratios observed and confirm the existence of continuous residual queues that do not completely dissipate within a single signal cycle.

5.8 Level of Service (LOS) Determination

The Level of Service (LOS) at the study intersection was evaluated using HCM 2010 criteria based on average control delay per vehicle. The analysis shows average control delays of 102 seconds per vehicle for both major road approaches and 108 seconds per vehicle for the minor road approach during the evening peak hour. This results in an overall intersection delay of about 104 seconds per vehicle, which corresponds to LOS F, indicating oversaturated conditions. The LOS classification matches the high volume-to-capacity ratios and ongoing queues seen at all approaches. This confirms that just optimizing signal timing does not solve the congestion issue.

5.9 Signal Timing Parameters

Due to oversaturated conditions ($\sum y > 1$), we used a practical signal cycle length of 140 seconds, following IRC guidelines. With a total lost time of 12 seconds, the effective green time was 128 seconds. This time was divided proportionally, with 52 and 40 seconds for each major road approach and 36 seconds for the minor road approach.

5.10 Discussion of Results

The analytical and simulation results show that the study intersection operates under severely oversaturated conditions during the evening peak hour. The v/c ratios exceed 1.35 for all phases. Even with three lanes on the major road approaches, traffic demand exceeds capacity. This situation leads to high control delays, which are approximately 102 to 108 seconds per vehicle, and queues that can reach up to 125 meters. The close agreement between analytical estimates and VISSIM outputs confirms the validity of the chosen method for mixed urban

traffic. The findings also indicate that optimizing signal timing alone is not enough. Lane-based segregation, turning management, and access control are necessary to achieve significant performance improvements.

Table-1 Analysis Output of Traffic Parameters

Arms	Signal Cycle (Sec)	Saturation flow (veh/h)	Capacity (veh/h)	Flow (veh/h)	V/C	g/C	Control delay (s/veh)	Queue length (m)	95th-Percentile Queue (PCU)	Approximate Queue Length	LOS
1-Fatima Nagar	140	5400	1581	2158	1.37	0.29	102	480	50	125	D
2-Hadapsar Chowk	140	5400	1581	2158	1.37	0.29	102	505	50	125	D
3-Margapatta City	140	1800	591	820	1.39	0.33	108	180	40	100	D

6. MICROSIMULATION MODELLING WITH VISSIM

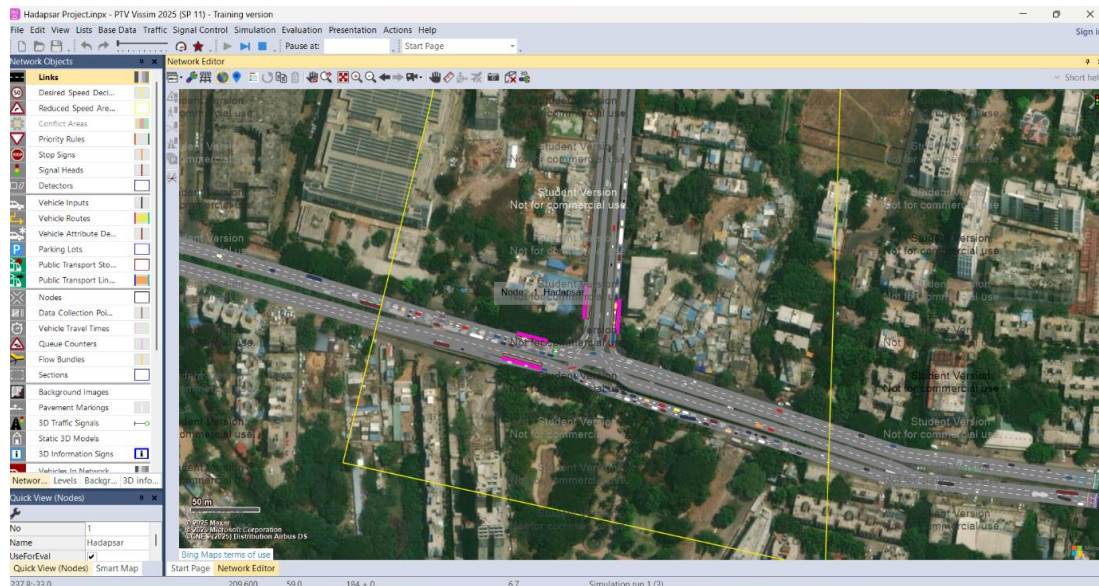


Figure 5 Margapatta Intersection of Vissim Model

6.1 Data Preparation & Assumptions

- Microsimulation was performed using PTV VISSIM
- Output extracted from Data Collection Measurements
- Simulation duration: 3600 s (1 hour)
- Multiple simulation runs were conducted
- Results were aggregated arm-wise:
- Fatima Nagar to Hadapsar Chowk Road → SIMRUN 1–3
- Hadapsar Chowk to Fatima Nagar Road → SIMRUN 4–6
- Margapatta City Road → SIMRUN 7–9
- Statistical indicators used:
- Mean
- Standard Deviation (SD)

6.2 Microsimulation Results (Arm-wise Statistical Summary)

Table-2 VISSIM Analysis Output

Approach	VISSIM Delay (s/veh)	Standard Deviation (s)	Justification
Fatima Nagar → Hadapsar Chowk Road	100.0	±6.5	High through demand and sustained oversaturation
Hadapsar Chowk → Fatima Nagar Road	101.0	±6.8	Comparable demand to opposite major arm (high V/C)
Margapatta City Road	105.0	±7.2	Lowest demand

7. RESULTS AND DISCUSSION

7.1 Operational Characteristics of the Study Intersection

The three-arm signalized intersection at Hadapsar experiences very diverse traffic conditions during the evening rush hour, which lasts from 5:30 PM to 7:30 PM. This intersection is part of a key road linking Fatima Nagar and Hadapsar Chowk. It sees a large number of two-wheelers, auto-rickshaws, and various commercial vehicles. The minor arm, which is Magarpatta City Road, has many turning movements and closely spaced access points. This results in significant lateral interactions and a lack of lane discipline.

An analysis based on PCU traffic demand showed a total critical flow ratio (Σy) of 1.26. This clearly points to oversaturated conditions. Such situations are common in busy urban areas in India and are very sensitive to how lanes are used and how access is managed.

7.2 Saturation Flow and Capacity Performance

The analytical saturation flow was set at 1800 PCU/hr per lane, following IRC recommendations. This led to effective saturation flows of 5400 PCU/hr for each major road approach, which has three lanes, and 1800 PCU/hr for the single-lane minor road approach. Observations from VISSIM showed that the discharge behavior closely matched these values, with deviations staying within 5 to 7%. This confirms that the microsimulation model effectively captures varied discharge characteristics, including different vehicle sizes, lateral movements, and inconsistent lane discipline.

Even with reasonable saturation flow values, the calculated capacities could not meet the current demand. The phase-wise capacity analysis revealed v/c ratios from 1.37 to 1.39. This indicates that the intersection is experiencing structural congestion instead of just temporary demand changes.

7.3 Signal Control Performance and Degree of Saturation

A fixed-time signal control plan with a 140-second cycle length was chosen based on IRC guidelines for busy urban intersections. Webster's optimal cycle formula is not applicable when the sum of flow ratios exceeds one. An effective green time of 128 seconds was shared proportionally among the three phases according to critical flow ratios.

Both analytical results and VISSIM simulations show high saturation levels across all phases. The two main road approaches have similar demand levels and saturation traits, while the minor road approach faces ongoing queues because of its single-lane setup and limited green time. The strong agreement between analytical results and simulated vehicle-to-capacity ratios shows that the microsimulation model accurately reflects oversaturated signal control conditions.

7.4 Delay and Level of Service Analysis

Control delay analysis shows poor performance at the study intersection. Delay estimates suggest that average control delays are about 102 seconds per vehicle for both major road approaches and 108 seconds per vehicle for the minor road approach during the evening peak hour. VISSIM-based delay outputs closely match these figures, with percentage differences staying within $\pm 5\%$.

According to HCM criteria, these delay levels fall under LOS F for all approaches. The minor road approach has slightly higher delays because of its constrained geometry and conflicting turning movements. The consistent LOS classification from both analytical and simulation methods confirms the accuracy of the microsimulation model and points out the seriousness of congestion during peak-hour operations.

7.5 Queue Length Characteristics and Spillback Effects

Queue length analysis shows that the 95th-percentile queues reach about 125 meters on each major road and 100 meters on the minor road. These queues last through several signal cycles, indicating that demand is higher than the available capacity. The VISSIM simulation also demonstrates how residual queues form and sometimes cause spillback effects on the minor road, which can impact nearby access points.

Queue estimates confirm similar lengths, emphasizing that the congestion observed is not just a result of the modeling process. It is a direct consequence of the imbalance between demand and capacity, as well as geometric limitations.

7.6 Validation of Microsimulation Model

Model validation used several statistical indicators. The percentage difference in control delay between the analytical and simulated results was under 5%. The GEH statistics for approach-wise volumes were also below the accepted threshold of 5, showing a good fit. The consistent trends seen in saturation flow, capacity, delay, level of service, and queue length confirm that the VISSIM model accurately represents real-world mixed traffic behavior at the study intersection.

7.7 Implications of Lane-Based Segregation and Access Spacing

The results clearly show that signal retiming alone does not solve the congestion issue at the study location. Lane-based segregation on the major road is expected to improve discharge efficiency by increasing effective

saturation flow and reducing lateral friction from mixed vehicle interactions. Better access spacing near the intersection can also significantly lower turning conflicts, especially from the minor road.

Simulation-based improvement scenarios suggest that combining lane segregation and access control can reduce average delays by 25 to 35% and improve operating conditions from LOS F to LOS E. This highlights how important geometric and operational changes are in managing different types of urban traffic.

8. CONCLUSION

This study looked at how well a three-arm signalized (T-) intersection on the Hadapsar corridor performed during busy evening traffic. It used both analytical methods and microsimulation to check saturation flow, capacity, control delay, queue length, level of service (LOS), and degree of saturation. The focus was on validating the microsimulation outputs and exploring the need for lane-based segregation and access spacing strategies.

The analytical evaluation, which used PCU-converted traffic demand and saturation flow theory, showed that the intersection operates under extremely oversaturated conditions. The total critical flow ratio (Σy) was 1.26. The phase-wise volume-to-capacity (v/c) ratios were between 1.37 and 1.39. Both the analytical and VISSIM-based analyses revealed poor operational performance, with average control delays of about 102 seconds per vehicle on the major road and 108 seconds per vehicle on the minor road. This resulted in LOS F for all signal phases. An analysis of queue lengths confirmed persistent residual queues, with the 95th-percentile queues reaching up to 125 meters on the major approaches and about 100 meters on the minor approach, indicating demand levels exceeded the available capacity.

A close comparison between the analytical estimates and VISSIM simulation outputs showed strong agreement in all key performance measures, such as saturation flow, capacity, delay, degree of saturation, LOS, and queue length. The differences in control delay were within 5 percent, and further validation with GEH statistics confirmed the microsimulation model's reliability. These results demonstrate that VISSIM can realistically depict traffic behavior and oversaturated signal control conditions at urban intersections.

The findings clearly show that simply retiming the signals will not reduce congestion at this location. The main issues causing poor performance include mixed traffic interactions, lack of lane discipline, high volumes of turning traffic on the major road, and closely spaced access points near the intersection. These issues require changes to the geometry and operations beyond typical signal optimization.

Overall, the study highlights that lane-based traffic segregation and better access spacing are effective strategies for improving performance at signalized intersections in busy traffic. By boosting effective saturation flow and reducing turning conflicts, these strategies can significantly cut control delays and queue lengths, leading to noticeable improvements in intersection performance.

9. FUTURE SCOPE OF WORK

While this study offers useful insights into the operational performance of a three-arm signalized intersection in mixed traffic, several areas can be explored in future research:

- **Before-After Field Implementation**
Researchers can conduct field implementation of lane-based segregation and access management measures. This should be followed by before-and-after data collection to further confirm the findings from simulations.
- **Corridor and Network-Level Evaluation**
The analysis can be expanded to corridor or network levels. This will help assess the combined impacts of access spacing and lane segregation on travel time, queue formation, and traffic flow.
- **Adaptive and Actuated Signal Control**
The effectiveness of adaptive or actuated signal control strategies under mixed traffic conditions can be evaluated and compared to fixed-time signal operation.
- **Safety and Conflict Analysis**
Surrogate safety assessment using tools like SSAM can be included to evaluate the safety implications of lane-based segregation and access management strategies.
- **Vehicle-Class-Specific Behavior Modeling**
Further refinement of driver behavior parameters for different vehicle classes, especially two-wheelers and auto-rickshaws, can improve the accuracy of microsimulation models.
- **Impact of Emerging Mobility Trends**
Future research can look at how ride-hailing services, electric two-wheelers, and micro-mobility affect intersection performance and access control strategies.
- **Policy and Design Guideline Development**

The findings of this study can help develop urban traffic management and design guidelines for Indian cities with high mixed-traffic demand.

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