



SUMO-Based Optimization of Intersection Performance under Heterogeneous Traffic

Md. Emtiaz Kabir¹, Mehruba Akter Sara², Md. Ibrahim Islam Ifty³, and Zaber Ahmed^{4*}

¹ Department of Civil Engineering, Atish Dipankar University of Science & Technology, Uttara, Dhaka-1230

* Correspondence: zaber_ce@adust.edu.bd

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Abstract: Traffic congestion is one of the most critical challenges in metropolitan cities, where intersections often experience long queues, high delays, and increased emissions due to mixed traffic and reliance on manual police control. This study examined how geometric improvements and signal timing optimization can improve the performance of a busy four-arm intersection in Uttara, Dhaka. Traffic data were collected through field surveys during peak hours and used to build a detailed microsimulation model in SUMO, which was calibrated against local driving behavior. Three scenarios were tested: the existing manual police control, channelization of turning lanes with current timings, and channelization with optimized fixed-time signals using Webster's method. Results showed that under current conditions, delays and queues were extremely high, corresponding to the lowest service level. Channelization alone reduced delays by up to 40% and improved overall flow. In contrast, the combination of channelization and optimized signals achieved the best outcomes, cutting delays to less than 40 seconds per vehicle, reducing queues by more than 70%, and improving the level of service to stable and acceptable conditions. An environmental analysis confirmed that the optimized scenario reduced fuel consumption and carbon emissions by 25–35% compared to current operations. These findings demonstrate that integrating physical improvements with evidence-based signal control can substantially enhance traffic efficiency, reduce energy use, and improve air quality in rapidly growing cities. The study provides practical insights for policymakers and planners seeking sustainable, low-cost solutions to congestion in Dhaka and other megacities facing similar challenges.

Keywords: Heterogeneous traffic; intersection performance; traffic signal optimization; SUMO microsimulation; urban traffic management

1. Introduction

Traffic congestion has become one of the most pressing urban challenges in Dhaka, Bangladesh, a megacity characterized by rapid urbanization, high population density, and increasing motorization [1]. According to recent studies, Dhaka consistently ranks among the most congested cities in the world, with travel speeds dropping sharply during peak periods, resulting in high economic, social, and environmental costs [2, 3]. Intersections, as the primary points of conflict and delay in road networks, are widely recognized as critical bottlenecks contributing to this chronic congestion problem [4].

A key feature of Dhaka's traffic environment is its diverse composition, including motorized vehicles such as buses, cars, trucks, motorcycles, and CNG three-wheelers alongside non-motorized rickshaws. The lack of lane discipline and weak enforcement further complicates traffic management at intersections. In many areas, traffic police rely on manual signal control, using hand signals to regulate traffic. While this approach offers flexibility during irregular traffic conditions, it often results in inconsistent green time allocation, reduced intersection efficiency, and significant delays during peak hours [5].

Globally, two strategies are commonly used to improve intersection performance: geometric channelization and traffic signal optimization. Channelization, which involves designating separate lanes for left-turn, right-turn, and through movements, reduces turning conflicts and increases discharge capacity. However, without coordinated signal control, its full potential remains limited. Signal optimization, on the other hand, ensures green times are allocated based on demand. Classical methods like Webster's are still popular in developing regions because of their simplicity and proven ability to decrease delays at intersections. Combining these two approaches — geometric improvements and optimized control — offers significant potential for sustainable congestion reduction, although this remains underexplored in Dhaka.

Recent advances in traffic microsimulation provide an opportunity to evaluate such integrated strategies under heterogeneous traffic conditions rigorously [6]. Simulation platforms such as VISSIM [7], AIMSUN [8], and SUMO [9] have been applied worldwide to assess intersection performance in complex traffic environments [10]. Among these, SUMO (Simulation of Urban Mobility) has proven particularly effective for developing cities due to its flexibility in modeling diverse vehicle classes, driver behaviors, and control schemes [11]. Several studies from India, Bangladesh, and Vietnam have shown that SUMO can realistically replicate mixed traffic dynamics when properly calibrated with local data [18-20]. Beyond operational efficiency, simulation-based studies also highlight the environmental benefits of improved traffic management, with optimized signals and channelization reducing fuel consumption and CO₂ emissions by 20–30% [15-17]. Despite this growing body of research, a clear gap remains in the Dhaka context. While some studies have examined either signal timing or geometric improvements in isolation [23, 24], very few have assessed their combined impact under heterogeneous traffic. Moreover, limited work has explored both operational and environmental implications, which are critical for a city facing both severe congestion and worsening air pollution.

To address this gap, the present study investigates the effectiveness of channelization and signal timing optimization at a major four-arm intersection in Uttara, Dhaka, using a calibrated SUMO microsimulation framework. A key contribution of this research is the rigorous calibration of the SUMO model using the Krauß car-following model, with locally observed traffic and driver-behavior parameters, explicitly tailored to Dhaka's heterogeneous, weakly lane-disciplined traffic conditions. Field-collected data were used to calibrate class-specific parameters for motorcycles, rickshaws, CNG three-wheelers, private cars, buses, trucks, and covered vans, and the model was validated against observed queue lengths and vehicle delays. This calibration-focused approach ensures that the simulated traffic dynamics closely represent real-world conditions, distinguishing the present study from generic microsimulation applications that rely on default parameter settings. Three operational scenarios were then analyzed: (i) the existing manual police control, (ii) channelization with observed signal timings, and (iii) channelization with optimized fixed-time signal control based on Webster's method. Performance was evaluated using multiple indicators, including delay, queue length, fuel consumption, CO₂ emissions, and level of service.

2. Methodology

The overall research methodology followed in this study is illustrated in Figure 1, which summarizes the sequential steps from data collection to model calibration, simulation, and performance evaluation. This framework ensured a systematic, reproducible approach to assessing intersection improvement strategies.

2.1 Study Area

The study was conducted at a four-arm intersection located in Uttara, Dhaka, one of the busiest sub-centers of the city, shown in Figure 2, where recurrent congestion is observed during peak hours. The selected

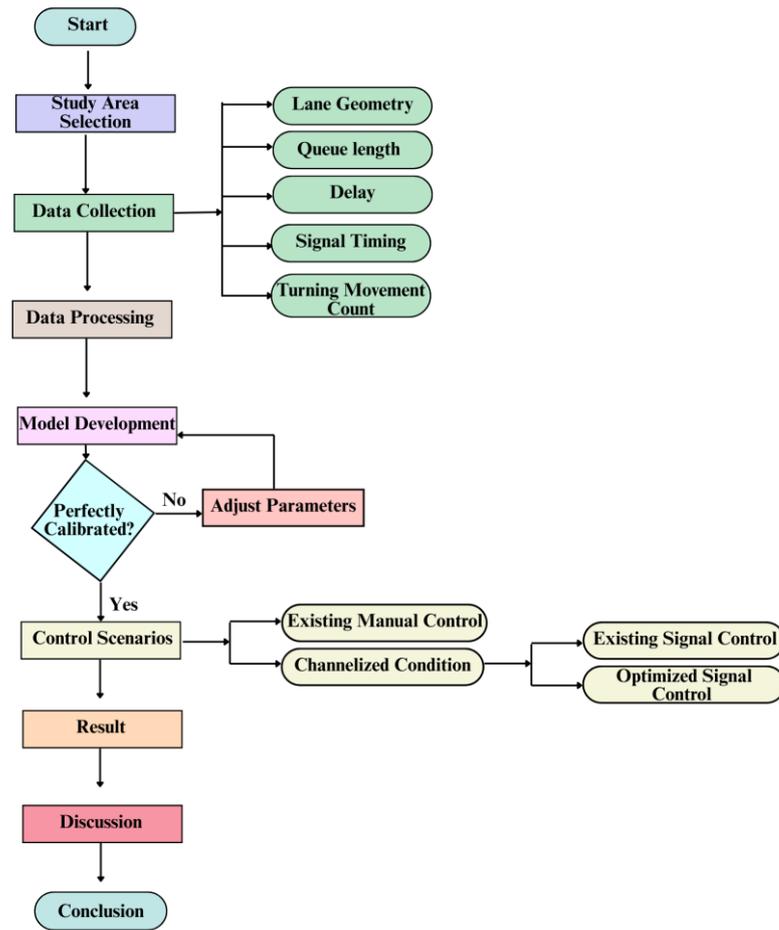


Figure 1. Research methodological framework outlining sequential steps from traffic data collection to model calibration, simulation, and performance evaluation.

Site experiences a heterogeneous traffic mix comprising buses, private cars, motorcycles, trucks, covered vans, CNG three-wheelers, and non-motorized rickshaws, typical of Dhaka’s traffic environment. The intersection currently operates under manual signal control, with traffic police regulating movements for turning and through traffic. The geometric details of the intersection, including the number of lanes and lane widths, were measured in the field and are summarized in Table 1.

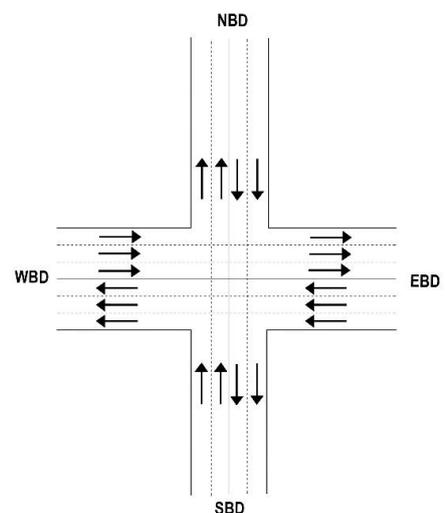
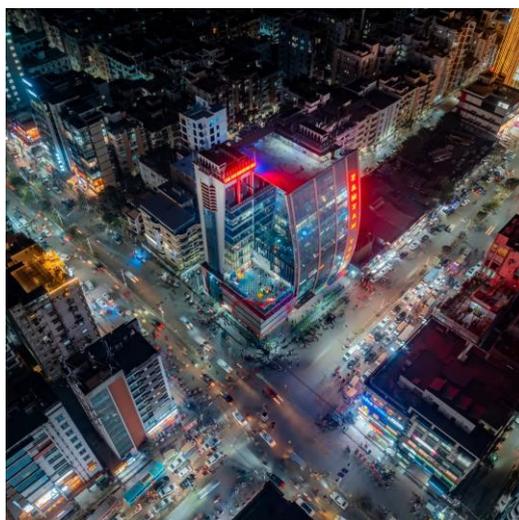


Figure 2. Study intersection at Zam Zam Tower, Uttara, Dhaka, showing approach lanes and geometric layout.

Table 1. Geometric characteristics of the study intersection

| Approach | Number of Lanes | Lane Width (m) |
|----------|-----------------|----------------|
| NBD | 2 | 3.5 |
| SBD | 2 | 3.5 |
| EBD | 3 | 3.5 |
| WBD | 3 | 3.5 |

2.2 Data Collection

Traffic data were collected using camera-based observation and manual counting across two peak periods: the weekday morning (08:00–09:00) and the evening (17:00–18:00) on Wednesday, 16th July, 2025. The selected day exhibited atypical dry day but realistic peak-period traffic patterns, capturing pronounced congestion conditions during both time windows. The surveys recorded detailed counts of turning movements for all approaches, disaggregated by vehicle class. Vehicles were counted manually from video footage to ensure accurate classification and movement tracking. In addition, average queue lengths (m) and average vehicle delays (s/veh) were manually measured on-site from direct field observations, while discharge rates were determined by observing the number of vehicles clearing the intersection during green phases under police control. The processed traffic data were converted into PCU using standard conversion factors [20], which are presented in Table 2 with vehicle dimensions [12]. The resulting total PCU values for each lane under different conditions are summarized in Table 3.

Table 2. Passenger Car Unit (PCU) equivalency factors and vehicle dimensions for heterogeneous traffic categories.

| Category of Vehicles | Attribute | Equivalent PCU Factors | | Dimensions | |
|----------------------------------|---|------------------------|---------------|------------|-------|
| | | 5% | 10% and above | Length | Width |
| Two-wheeler (Motorcycle/Scooter) |  | 0.5 | 0.75 | 1.9 | 0.6 |
| Bus |  | 2.2 | 3.7 | 10.6 | 2.5 |
| Passenger Car |  | 1.0 | 1.0 | 4.6 | 1.7 |
| Rickshaw |  | 1.2 | 2.0 | 2.3 | 1.5 |
| Truck |  | 2.2 | 3.7 | 7.5 | 2.5 |
| CNG |  | 1.2 | 2.0 | 2.9 | 1.8 |
| Covered Van |  | 1.4 | 2.0 | 5.5 | 2 |

2.3 Car-Following Model

In this study, the Krauß car-following model was implemented in SUMO to simulate longitudinal vehicle interactions. This model captures how a following vehicle adjusts its speed in response to the leading vehicle's behavior, accounting for driver reaction time, acceleration/deceleration limits, and stochastic imperfections.

The basic formulation is expressed as:

$$\frac{dv_i(t)}{dt} = \frac{v_n(t) - v_{n-1}(t)}{\tau} \quad (1)$$

where $v_n(t)$ is the speed of the leading vehicle, $v_{n-1}(t)$ is the speed of the following vehicle, $v_i(t)$ denotes the instantaneous speed of vehicle i . and τ is the driver's reaction time.

The safe velocity is calculated as:

$$v_{\text{safe}}(t) = v_l(t) + \frac{g(t) - g_{\text{des}}(t)}{\tau_b + \tau} \quad (2)$$

Table 3. PCU flows by vehicle type and approach during weekday morning and evening peak periods.

| Vehicle Type | Source Lane | NBD | WBD | SBD | EBD | NBD | WBD | SBD | EBD |
|--------------|-------------|--------------|-------|-------|-------|--------------|-------|-------|------|
| | | Morning Peak | | | | Evening Peak | | | |
| Bus | | 0 | 11 | 0 | – | 0 | 46.2 | 0 | – |
| Private Car | | 18 | 218 | 34 | – | 34 | 206 | 33 | – |
| CNG | | 2.4 | 39.6 | 3.6 | – | 21.6 | 58.8 | 14.4 | – |
| Motorcycle | EBD | 2.25 | 35.25 | 2.25 | – | 13.5 | 51.75 | 18 | – |
| Truck | | 0 | 8.8 | 4.4 | – | 4.4 | 26.4 | 6.6 | – |
| Covered Van | | 2.8 | 28 | 8.4 | – | 4.4 | 44 | 13.2 | – |
| Rickshaw | | 248 | 336 | 164 | – | 44 | 300 | 160 | – |
| Bus | | 0 | 0 | – | 0 | 0 | 0 | – | 0 |
| Private Car | | 30 | 181 | – | 47 | 27 | 168 | – | 40 |
| CNG | | 4.8 | 13.2 | – | 8.4 | 6 | 19.2 | – | 9.6 |
| Motorcycle | SBD | 7.5 | 23.25 | – | 20.25 | 6.75 | 18.75 | – | 13.5 |
| Truck | | 0 | 4.4 | – | 0 | 4.4 | 4.4 | – | 0 |
| Covered Van | | 7 | 8.4 | – | 9.8 | 8.4 | 16.8 | – | 30.8 |
| Rickshaw | | 116 | 264 | – | 116 | 224 | 224 | – | 140 |
| Bus | | 0 | – | 13.2 | 0 | 0 | – | 35.2 | 0 |
| Private Car | | 37 | – | 159 | 23 | 38 | – | 121 | 38 |
| CNG | | 1.2 | – | 16.8 | 1.2 | 12 | – | 46.8 | 8.4 |
| Motorcycle | WBD | 4.5 | – | 64.5 | 9 | 9 | – | 50.25 | 13.5 |
| Truck | | 4.4 | – | 17.6 | 0 | 13.2 | – | 30.8 | 13.2 |
| Covered Van | | 4.2 | – | 8.4 | 2.8 | 2.8 | – | 21 | 9.8 |
| Rickshaw | | 108 | – | 288 | 194 | 204 | – | 362 | 272 |
| Bus | | – | 0 | 0 | 0 | – | 0 | 0 | 0 |
| Private Car | | – | 20 | 155 | 25 | – | 18 | 350 | 223 |
| CNG | | – | 6 | 9.6 | 2.4 | – | 4.8 | 8.4 | 2.4 |
| Motorcycle | NBD | – | 7.5 | 12.75 | 7.5 | – | 6.75 | 11.25 | 6.75 |
| Truck | | – | 4.4 | 13.2 | 11 | – | 4.4 | 11 | 8.8 |
| Covered Van | | – | 4.2 | 9.8 | 2.8 | – | 4.2 | 8.4 | 2.8 |
| Rickshaw | | – | 148 | 260 | 182 | – | 134 | 234 | 274 |

where $v_l(t)$ is the speed of the leader, $g(t)$ is the actual spacing between vehicles, $g_{des}(t)$ is the desired gap, and τ_b represents the braking reaction time. The spacing is given by:

$$g(t) = x_l - x_f - l \tag{3}$$

with $x_l(t)$ and $x_f(t)$ denoting the positions of the leader and follower, respectively, and l the vehicle length.

The desired velocity is

$$v_{des} = \min[v_{max}, v_t + a(v)\Delta t, v_{safe}(t)] \tag{4}$$

where v_{des} is the desired velocity, v_{max} is the maximum allowable speed, v_t is the current speed, $a(v)$ is the acceleration function, Δt is the simulation time step, and v_{safe} is the safe speed.

Finally, the updated vehicle velocity with stochastic variation is:

$$v(t + \Delta t) = \max\{ 0, v_{des}(t) - \eta \} \tag{5}$$

where η is a random noise term representing driver imperfection.

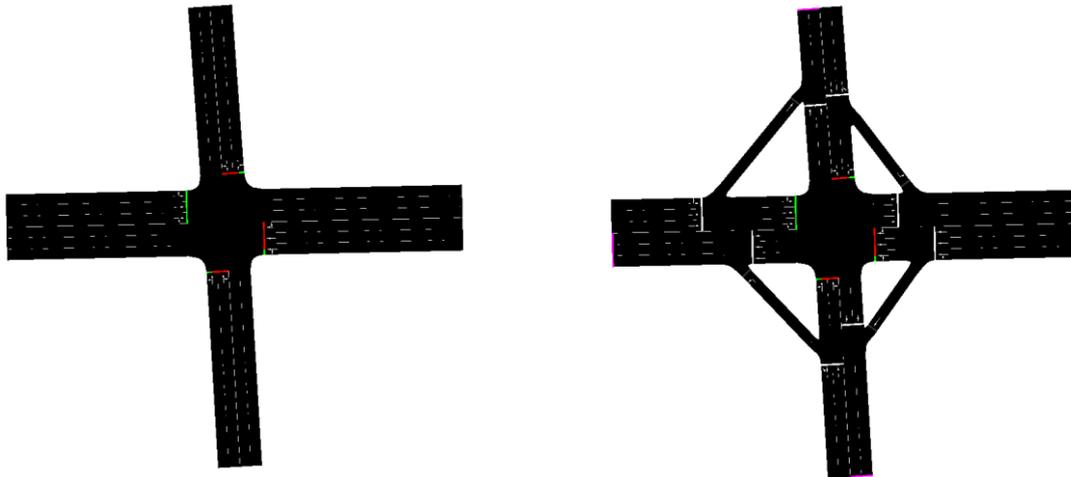


Figure 3. Network development in SUMO illustrating baseline (non-channelized) and channelized control strategies.

2.4 Network Development in SUMO

The intersection was modeled in SUMO using NetEdit, incorporating the exact geometric details such as lane widths, approach lengths, and turning connections. Vehicle flows were generated in the .rou.xml file based on observed turning counts, while multiple vehicle classes were defined with specific parameters for length, acceleration, deceleration, and maximum speed to represent the heterogeneous traffic conditions of Dhaka realistically. Figure 3 shows the developed network with baseline and channelized control strategies.

2.5 Model Calibration and Validation

The SUMO microsimulation was calibrated to replicate the field-observed traffic dynamics of the study intersection, with emphasis on queue formation and per-vehicle delay as the primary performance indicators. The model incorporated the heterogeneous vehicle fleet (motorcycles, cars, CNG three-wheelers, rickshaws, covered vans, buses, and trucks), and class-specific attributes were assigned based on field observations and regional literature [12]. The calibration and validation process is described below.

2.5.1 Representation of Vehicle Classes

Each vehicle class was explicitly represented with parameters for length, acceleration, deceleration, and desired speed to reflect local traffic characteristics. For example, rickshaws and CNGs were modeled with shorter lengths and lower speeds, while buses and trucks were assigned lower acceleration/deceleration envelopes.

2.5.2 Calibration Parameters

Model calibration was treated as a central component of this study rather than a routine preprocessing step, given the complexity of heterogeneous traffic and weak lane discipline observed at the study intersection. Calibration focused on car-following and lane-changing parameters, as they significantly influence mixed-traffic dynamics in Dhaka. The explored parameter ranges and the corresponding calibrated values are summarized in Table 4. The following aspects were systematically adjusted:

Car-following (τ , σ): Time-headway (τ) was varied within class-specific ranges (motorcycles: 0.7–0.9 s, rickshaws: 0.6–0.8 s, cars: 1.0–1.2 s, covered-vans: 1.2–1.5 s, buses/trucks: 1.5–2.0 s). Driver randomness (σ) was explored between 0.5 and 0.8 to capture weak lane discipline.

Lane-changing (minGap, aggressiveness): Minimum gaps for lane-change checks were reduced (0.3–0.7 m), while strategic aggressiveness was modestly increased (+10–30%) to reproduce opportunistic weaving.

Speed & Dynamics (vType): Desired speeds were set — Motorcycle (9.7 m/s), Rickshaw (3.3 m/s), Car (6.9 m/s), Covered Van (5.6 m/s), Bus (5.0 m/s), and Truck (4.2 m/s) — with uniform acceleration (2.8 m/s²) and deceleration (1.9 m/s²) applied across all vehicle types to ensure consistent calibration of movement dynamics [12].

Table 4. Calibrated SUMO model parameters for different vehicle classes with explored ranges and final selected values.

| Parameter (SUMO name) | Vehicle class | Explored range | Final calibrated value |
|-----------------------------|---------------|----------------|------------------------|
| tau (s) | Motorcycle | 0.7 – 0.9 | 0.8 |
| | Rickshaw | 0.6 – 0.8 | 0.7 |
| | Car | 1.0 – 1.2 | 1.1 |
| | Covered van | 1.2 – 1.5 | 1.3 |
| | Bus & Truck | 1.5 – 2.0 | 1.6 |
| sigma (driver imperfection) | All classes | 0.5 – 0.8 | 0.65 |
| minGap (m) | All classes | 0.3 – 0.7 | 0.45 |

Vehicle lengths: Adjusted to reflect the local fleet, with motorcycles, rickshaws, and CNGs shorter than cars, and Cavad vans intermediate, shown in Table 2.

2.5.3 Calibration Procedure

Calibration followed an iterative and structured process in which one parameter family (e.g., car-following) was varied at a time, and the resulting model outputs in terms of average queue length and delay were compared against field data. Parameter sets that improved fit across approaches were retained, and the process was repeated until the simulated queue lengths (m) and delays (s/veh) closely matched observed values. Goodness-of-fit was evaluated using the Root Mean Square Error (RMSE) for queue length and the Mean Absolute Percentage Error (MAPE) for delay. Calibration was deemed satisfactory once both metrics fell below the accepted microsimulation threshold of $\leq 15\%$.

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\text{Simulated}_i - \text{Observed}_i)^2} \quad (6)$$

$$\text{MAPE} = \frac{100}{n} \sum_{i=1}^n \frac{|\text{Simulated}_i - \text{Observed}_i|}{\text{Observed}_i} \quad (7)$$

2.5.4 Validation

To prevent overfitting, validation was performed using hold-out field data. A one-traffic-phase segment from each peak-hour observation, excluded during calibration, was used for model validation. Multiple stochastic replications confirmed robustness. The model's ability to reproduce average queue lengths and delays at each approach was assessed and summarized in Table 5.

Table 5. Validation results comparing observed and simulated average queue lengths and vehicle delays for each intersection approach.

| Approach | Average Queue Length | | | Average Delay | | |
|------------|----------------------|---------------|---------|------------------|-------------------|---------|
| | Observed (m) | Simulated (m) | % Error | Observed (s/veh) | Simulated (s/veh) | % Error |
| Northbound | 38 | 42 | 10.53% | 106 | 112 | 5.66% |
| Southbound | 35.3 | 38 | 7.65% | 87 | 92 | 5.75% |
| Eastbound | 34.8 | 36 | 3.45% | 83 | 88 | 6.02% |
| Westbound | 31.2 | 34 | 8.97% | 74 | 79 | 6.76% |

Additionally, sensitivity tests were conducted by varying τ and σ by $\pm 10\%$. The qualitative ranking of the three strategies (baseline, channelised, Webster) remained unchanged, confirming stability of results under plausible behavioral uncertainty.

The validation results indicate that the simulation model reasonably replicates observed traffic conditions, with an RMSE of 2.24 m for queue lengths and 4.1 s/veh for vehicle delays, and MAPE of 7.15% and 6.05% for queues and delays, respectively.

2.5.5 Emission modeling in SUMO

CO₂ emissions were estimated using SUMO’s HBEFA-based emission model, which calculates instantaneous emissions as a function of vehicle speed and acceleration. Each heterogeneous vehicle class was mapped to an appropriate HBEFA emission category based on its size and operating characteristics. Emission outputs were generated directly from SUMO using the .emission.xml output file, which records per-vehicle emission rates at each simulation step. The reported CO₂ values (mg/s) represent average emission rates aggregated across all vehicles and simulation replications for each control scenario and peak period.

2.6 Control Scenarios

To ensure a consistent and transparent evaluation, three traffic control conditions were developed and tested in SUMO. Each scenario reflects a different level of intervention, ranging from the current observed operation to proposed engineering and signalization strategies.

2.6.1 Existing Manual Control (Baseline)

Field observations confirmed that the intersection is operated manually by police officers, without any fixed cycle length. Green time allocations varied according to the officer’s discretion, traffic volume, and congestion levels. However, to simulate this condition in SUMO, the observed timings were averaged for each approach and used as a representative baseline signal plan, as shown in Table 6.

Table 6. Average observed green times under manual police control for each intersection approach.

| Approach | Avg. Green (s) | Range Observed (s) |
|----------------------------|----------------|--------------------|
| Northbound Direction(NBD) | 55 | 30–120 |
| Southbound Direction (SBD) | 60 | 40–110 |
| Eastbound Direction (EBD) | 50 | 35–100 |
| Westbound Direction (WBD) | 65 | 45–115 |

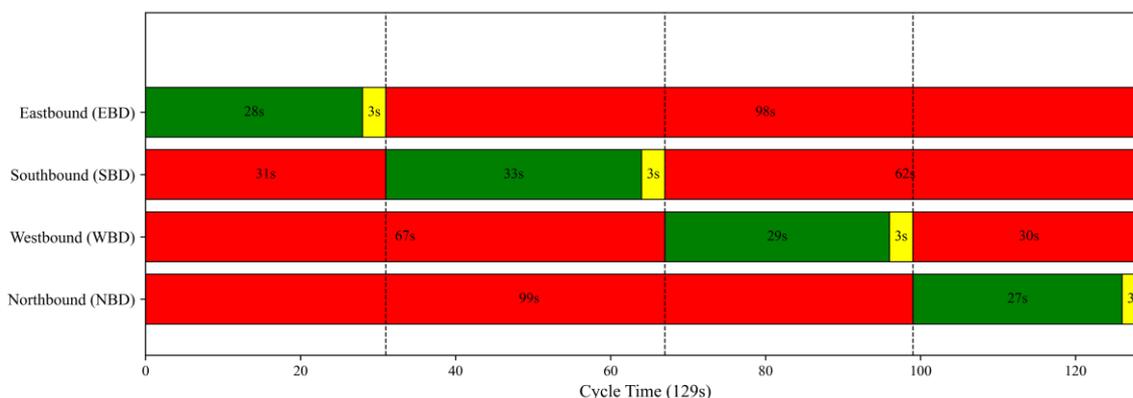


Figure 4. Optimized fixed-time signal plan for the study intersection, designed using Webster’s method.

The baseline simulation was configured in SUMO using the average green splits observed in the field, without applying any fixed cycle optimization. All turning and through movements were allowed within the same green phase, as no channelization was introduced. This setup was designed to replicate the irregular and discretionary nature of manual police control while providing a consistent and reproducible baseline against which alternative signal control strategies could be evaluated.

2.6.2 Channelized Condition

In this scenario, geometric improvements were implemented without altering the overall control type. Dedicated lanes were introduced for left-turn and through movements on each approach, reducing blocking conflicts and enhancing lane discharge capacity. Channelization improved lane discipline and ensured more efficient utilization of the available green time. Two signal control strategies were tested under the channelized configuration:

Existing Signal Control: The same average observed green times (Table 6) were applied to replicate the manual officer-based control. This setup allowed the assessment of benefits achieved solely through geometric improvements, without altering the signal timing plan.

Optimized Signal Control (Webster’s Method): A fixed-time signal plan was designed using Webster’s formula:

$$C = \frac{1.5L + 5}{1 - \sum y} \tag{8}$$

where L represents the total lost time per cycle (s), and $\sum y$ is the sum of critical flow ratios. The resulting optimal cycle length was then allocated into green splits proportional to the critical lane-group flows. A multiphase plan was developed to ensure safe sequencing of turning and through traffic movements, as illustrated in Figure 4. This condition represents a fully engineered traffic signalization strategy aimed at minimizing average delay and maximizing overall intersection efficiency.

Table 7. Intermediate parameters and phase-wise signal timing obtained using Webster’s method for the optimized channelized intersection.

| Phase | Approach | Lanes | Saturation Flow (PCU/h/lane) | yi | Effective Green (s) | Lost time (s) | Adopted cycle length (s) |
|-------|------------------|-------|------------------------------|------|---------------------|---------------|--------------------------|
| 1 | Eastbound (EBD) | 3 | 1890 | 0.20 | 28 | 3 | 129 |
| 2 | Southbound (SBD) | 2 | 1890 | 0.24 | 33 | 3 | |
| 3 | Westbound (WBD) | 3 | 1890 | 0.20 | 29 | 3 | |
| 4 | Northbound (NBD) | 2 | 1890 | 0.18 | 27 | 3 | |

Table 7 summarizes the key parameters and results of the signal timing optimization for the channelized intersection. It presents the saturation flow rates assumed for each approach, the corresponding critical flow ratios (yi), and the effective green times allocated to each phase based on demand. A uniform lost time of 3 s per phase is assumed, yielding an optimized common cycle length of 129 s. The distribution of effective green times reflects the relative traffic demand of each approach: the southbound approach receives the highest green time due to its larger critical flow ratio. In contrast, the remaining approaches are allocated comparable green times consistent with their respective yi values.

Table 8. Level of Service (LOS) classification based on average vehicle control delay according to HCM standards.

| LOS | Average Control Delay (s/veh) | Description |
|-----|-------------------------------|--|
| A | ≤ 10 | Free flow; very little delay, high comfort. |
| B | > 10 – 20 | Stable flow; short delays, acceptable operations. |
| C | > 20 – 35 | Stable flow; noticeable delays, satisfactory operations. |
| D | > 35 – 55 | Approaching unstable flow; longer delays, tolerable for short periods. |
| E | > 55 – 80 | Unstable flow; very long delays, operating near capacity. |
| F | > 80 | Forced/unacceptable flow; breakdown conditions with excessive delays. |

2.7 Simulation Experiments

Simulations were run for each control strategy across the four defined traffic periods, with multiple replications to minimize stochastic variability and ensure reliable results. The evaluation was based on key performance indicators, including average queue length (m), average vehicle delay (s/veh), fuel consumption (mg/veh), and CO₂ emissions (mg/veh). These performance measures enabled a comprehensive assessment of the intersection's operational efficiency and environmental impacts under different management strategies. Later, the Level of Service (LOS) was evaluated from the Average Vehicle delay [21]. The standard chart for finding LOS is given in Table 8.

3. Results

3.1 Average Queue Length

The simulation results reveal notable variations in queue lengths across the three operational scenarios, as illustrated in Figure 5. During the morning peak, the Current scenario exhibits severe congestion, with the Southbound (44.08 m), Eastbound (42.68 m), and Northbound (42.42 m) approaches

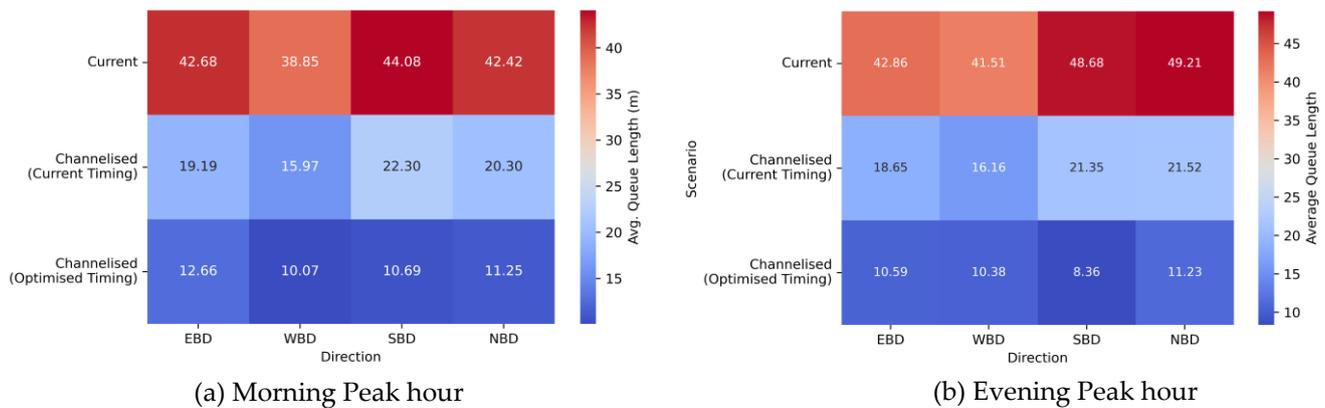


Figure 5. Average queue length across four approaches under three control strategies

experiencing the longest queues. Introducing channelization under existing timings substantially alleviates congestion, reducing queues to within 15–22 m. The greatest improvement, however, is observed under the Channelized with Optimized Timing scenario, where all approaches fall below 13 m, with Eastbound achieving the minimum at 12.66 m.

Evening peak conditions demonstrate heightened traffic demand, leading to longer queues overall. Under the Current scenario, Northbound (49.21 m) and Southbound (48.68 m) approaches display critical bottlenecks. Channelization moderates these queues to a range of 16–22 m, while optimization reduces them further to 8.36–11.23 m, the Southbound approach recording the lowest. Comparatively, queues are consistently higher in the evening; nevertheless, the combined effect of channelization and optimized timings delivers reductions exceeding 70% relative to the baseline, underscoring the role of integrated strategies in enhancing operational efficiency.

3.2 Average Vehicle Delay

The analysis of average vehicle delays further reinforces the trends observed in queue length performance, as illustrated in Figure 6. During the morning peak period, the Current scenario exhibits excessive delays across all approaches, particularly severe impacts on Eastbound and Northbound movements, with average delays of approximately 150 s and 134 s, respectively. The introduction of geometric channelization while retaining existing signal timings results in measurable performance improvements, most notably on the Eastbound approach, where average delay is reduced to about 102 s. However, residual congestion persists on several approaches, indicating that geometric improvements alone are insufficient to address operational inefficiencies fully. The application of optimized signal timing in conjunction with channelization yields substantial additional benefits, reducing average delays on all approaches to below 40 s. This improvement reflects a more balanced allocation of green time that better matches approach-specific demand, resulting in smoother traffic progression and reduced intersection delay during the morning peak.

During the evening peak period, traffic demand increases considerably, leading to more pronounced congestion and systematically higher delays than in the morning. Under the Current scenario, delays reach critical levels, with eastbound traffic experiencing an average delay of approximately 165 s and northbound traffic around 148 s. Although channelization under existing timings provides partial relief, it does not fully mitigate the intensified congestion or eliminate the performance gap between morning and evening conditions. In contrast, the optimized signal timing strategy remains highly effective under heavier demand, reducing average delays to a narrow range of 31–41 s across all approaches. Overall, the findings indicate that

while evening peak conditions inherently impose greater operational stress on the intersection, the combined implementation of channelization and optimized signal timing consistently delivers substantial delay reductions. This demonstrates the robustness of the proposed strategy and its ability to maintain acceptable service levels even under high-demand, heterogeneous traffic conditions.

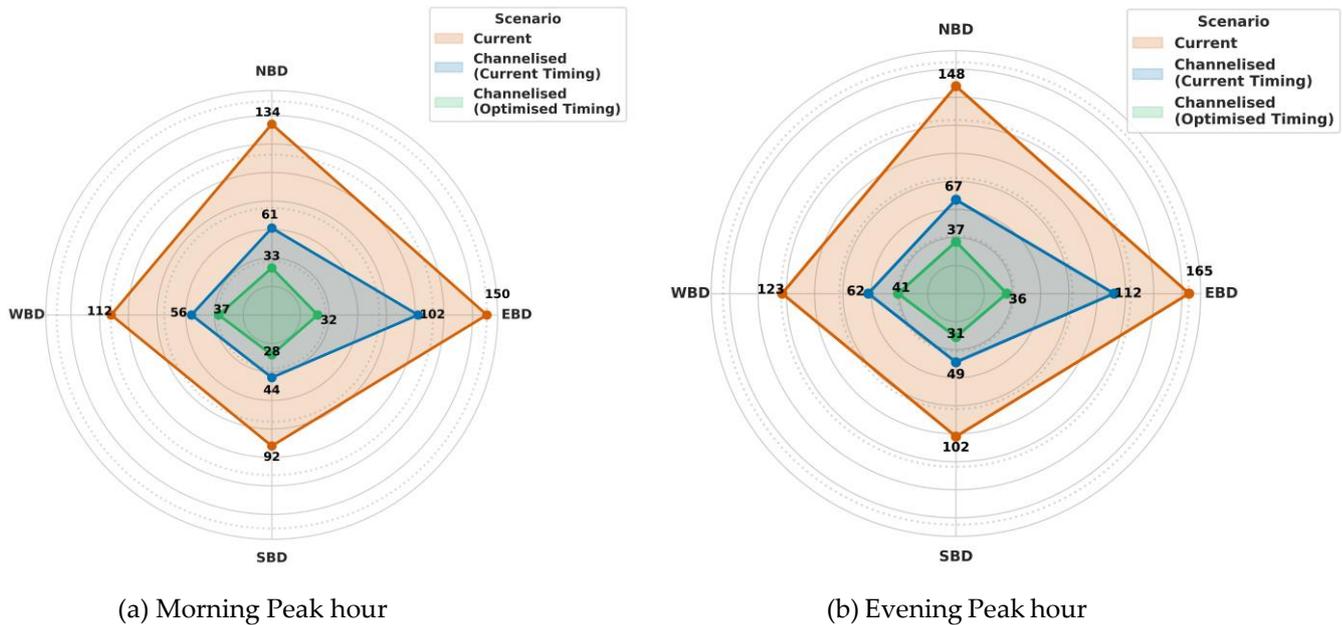
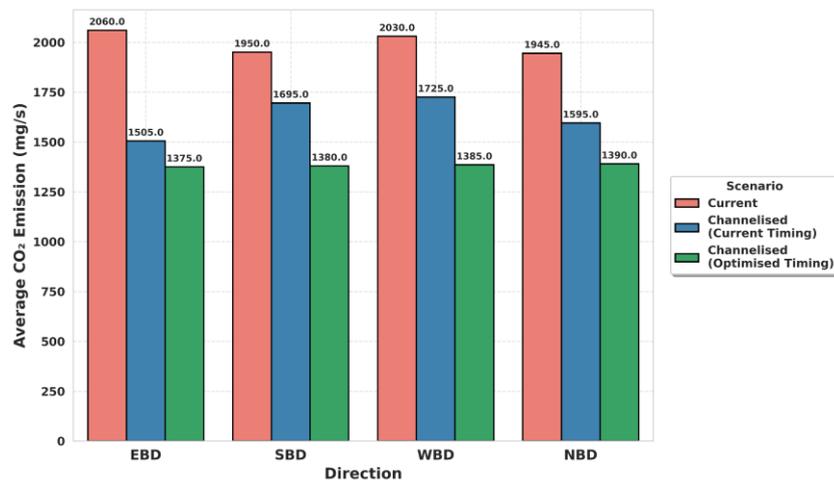


Figure 6. Average vehicle delay (s) across four approaches under different control strategies

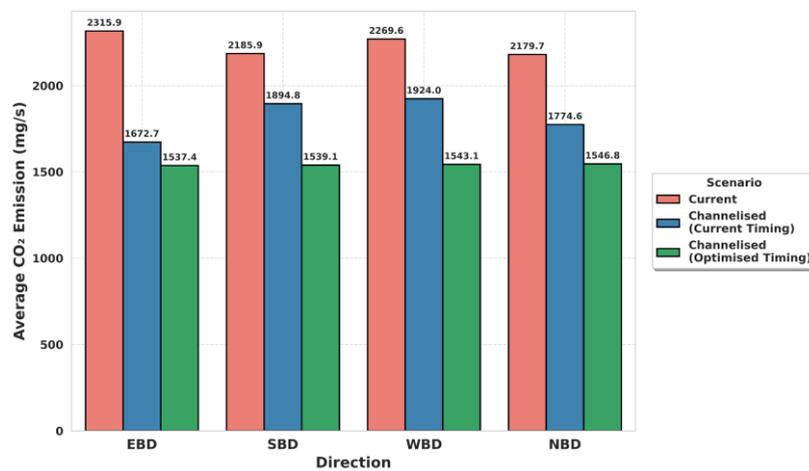
3.3 Carbon Dioxide Emissions

The analysis of average CO₂ emissions, illustrated in Figure 7, further highlights the efficiency gains achieved through the combined application of geometric and signal-control improvements. Under the Current scenario, emissions remain consistently high, exceeding 2,100 mg/s across all approaches, with the Eastbound approach reaching a peak value of 2,315.89 mg/s, reflecting prolonged idling, frequent stops, and inefficient queue discharge. The introduction of channelization reduces emissions to a range between 1,672.65 mg/s on the Eastbound approach and 1,924.01 mg/s on the Westbound approach, indicating that geometric reconfiguration alone can partially mitigate unnecessary idling and improve vehicle progression. These reductions are consistent with the observed decreases in queue lengths and delays, confirming the strong linkage between operational efficiency and emission performance. However, the remaining emission levels suggest that further improvements require complementary signal optimization to fully exploit the benefits of geometric interventions under heterogeneous traffic conditions.

The most substantial reductions are achieved in the Channelized with Optimized Timing scenario, where emissions converge to a narrow band of 1,537–1,547 mg/s across all directions. This outcome reflects the synergistic effect of smooth traffic progression and reduced stop-and-go operations. Although evening peaks generate slightly higher emissions than morning peaks, consistent with longer delays and queues, the optimized channelization scenario reduces emissions by 25–35% relative to the Current scenario. These findings confirm the dual benefits of traffic management strategies: improving operational efficiency while reducing environmental impacts.



(a) Morning Peak hour

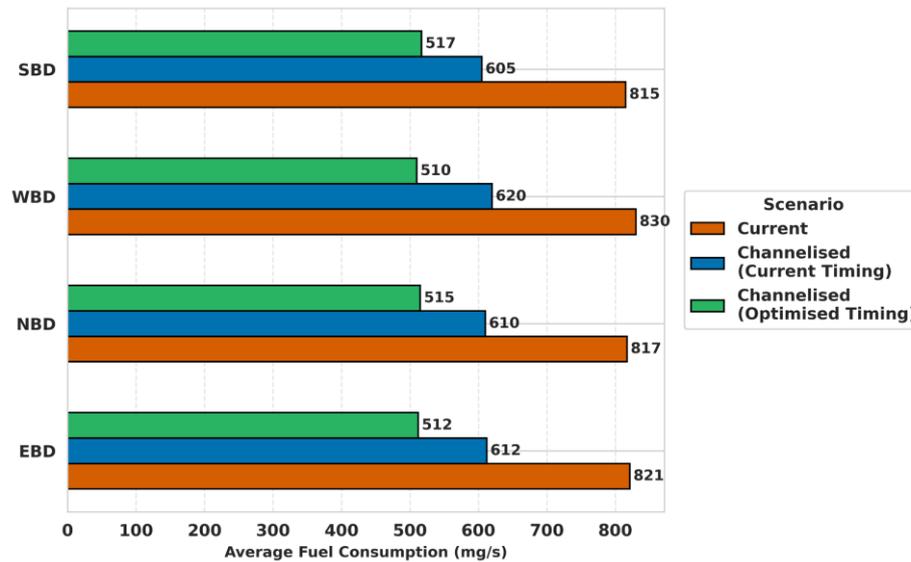


(b) Evening Peak hour

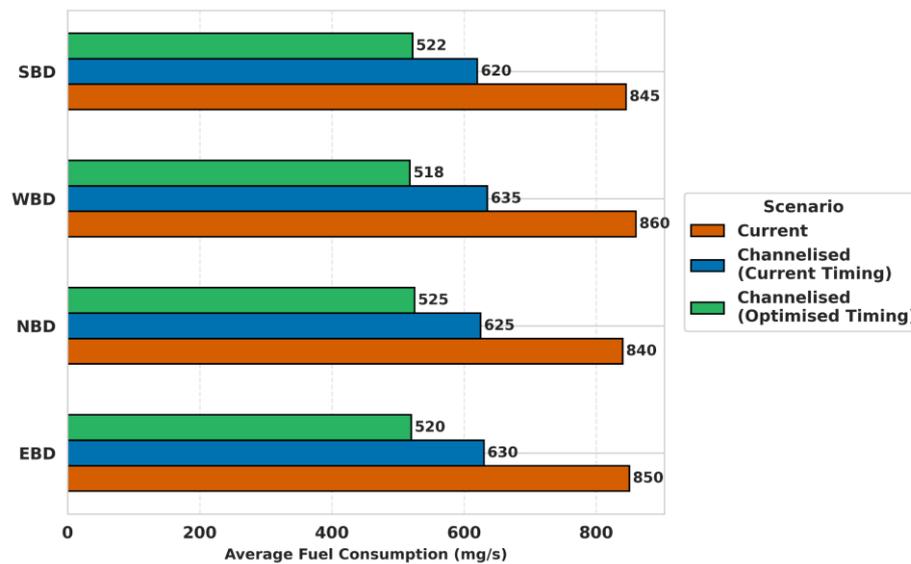
Figure 7. Average CO₂ emissions by approach for each control strategy

3.4 Fuel Consumption

Fuel consumption patterns mirror those of delay and emissions. In both the morning and evening peaks, the Current scenario yields the highest consumption, with all approaches exceeding 815 mg/s in the morning and rising to 860 mg/s in the evening, as shown in Figure 8. Channelization under existing timings reduces these values by approximately 200–220 mg/s, while the addition of optimized timings contributes a further reduction of 90–110 mg/s. Evening conditions consistently lead to higher fuel consumption, attributable to higher traffic volumes and longer idling times. For example, the Westbound approach records 830 mg/s in the morning under the Current scenario, increasing to 860 mg/s in the evening. Similar differences are evident across other approaches. Despite this, the optimized channelization strategy consistently outperforms alternatives, minimizing idling and smoothing discharge flows. These results underline the importance of combining physical and control measures not only for congestion relief but also for reducing energy consumption at urban intersections.



(a) Morning Peak hour



(b) Evening Peak hour

Figure 8. Average fuel consumption across four approaches under three control strategies

3.5 Comparative performance and statistical significance

Table 9 compares the performance of the three control strategies under repeated simulation runs for both morning and evening peak hours. The results show a clear and consistent reduction in average delay, queue length, CO₂ emissions, and fuel consumption as the control strategy progresses from the current manual operation to channelization and finally to channelization with optimized signal timing.

During the morning peak, average delay decreases from 128.6 s/veh under current control to 89.3 s/veh with channelization, and further to 32.4 s/veh under optimized control. A similar pattern is observed for queue length, which reduces from 42.9 m to 18.7 m and then to 12.1 m. Environmental indicators follow the same trend, with CO₂ emissions and fuel consumption dropping steadily across the three scenarios. Evening peak conditions show higher absolute values due to increased demand; however, the relative improvements remain consistent, with optimized control producing the lowest delays (35.7 s/veh), the shortest queues (10.4 m), and the lowest emission and fuel consumption levels. The values in Table 9 are reported as mean ± standard

deviation, based on 10 independent simulation replications, which capture the inherent stochastic variability of microsimulation. To verify that the observed differences between scenarios are not due to random effects, a one-way ANOVA was applied separately for each performance indicator and peak period. The resulting p-values (< 0.001 for all cases) indicate that the differences in operational and environmental performance between the control strategies are statistically significant. This confirms that the improvements achieved through channelization and optimized signal timing are systematic and reproducible rather than incidental.

Table 9. Statistical comparison of delay, queue length, emissions, and fuel consumption across control scenarios for morning and evening peak hours.

| Duration | Performance Indicator | Current Control (Mean ± SD) | Channelized (Mean ± SD) | Channelized + Optimized (Mean ± SD) | ANOVA (p-value) |
|-------------------|----------------------------------|-----------------------------|-------------------------|-------------------------------------|-----------------|
| Morning peak hour | Average Delay (s/veh) | 128.6 ± 7.2 | 89.3 ± 5.8 | 32.4 ± 4.9 | < 0.001 |
| | Average Queue Length (m) | 42.9 ± 3.0 | 18.7 ± 2.2 | 12.1 ± 1.8 | < 0.001 |
| | CO ₂ Emissions (mg/s) | 2148 ± 81 | 1769 ± 69 | 1568 ± 58 | < 0.001 |
| | Fuel Consumption (mg/s) | 818 ± 49 | 602 ± 38 | 521 ± 34 | < 0.001 |
| Evening peak hour | Average Delay (s/veh) | 154.3 ± 7.8 | 102.4 ± 6.1 | 35.7 ± 5.3 | < 0.001 |
| | Average Queue Length (m) | 48.6 ± 3.2 | 19.8 ± 2.4 | 10.4 ± 1.9 | < 0.001 |
| | CO ₂ Emissions (mg/s) | 2315 ± 88 | 1821 ± 72 | 1542 ± 61 | < 0.001 |
| | Fuel Consumption (mg/s) | 862 ± 54 | 648 ± 41 | 512 ± 36 | < 0.001 |

4. Discussion

The simulation results clearly demonstrate the impact of channelization and signal timing optimization on intersection performance. In the Current scenario, the average queue lengths and vehicle delays were unacceptably high, particularly during the evening peak, where Northbound and Southbound queues reached 49.21 m and 48.68 m, respectively, and delays exceeded 160 s/vehicle. According to the HCM methodology, these conditions correspond to Level of Service (LOS) F, as shown in Figure 9, indicating unstable traffic flow, frequent stop-and-go conditions, and extreme driver discomfort. Such performance highlights the limitations of unstructured traffic management and manual signal control.

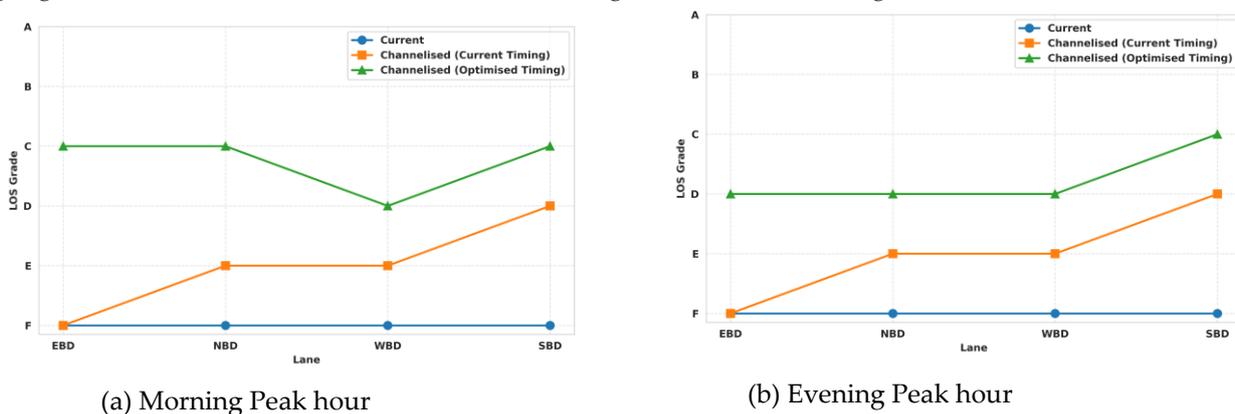


Figure 9. Intersection Level of Service (LOS) classification for under alternative scenarios.

Introducing channelization with existing timings substantially improved operational efficiency. Queues were reduced to 15–22 m in the morning and 16–22 m in the evening, and delays decreased by approximately 30–40%. These improvements generally correspond to LOS D, reflecting stable flow with occasional delays. Although this scenario shows clear benefits over the baseline, it remains sensitive to peak-period demand, particularly in the evening, suggesting that physical modifications alone cannot fully alleviate congestion.

The Channelized with Optimized Timing scenario produced the most significant gains. Average queue lengths fell below 13 m in the morning and to 8–11 m in the evening, while delays were limited to 31–41 s across approaches. From an LOS perspective, these outcomes correspond to LOS C, indicating stable flow, acceptable driver comfort, and manageable delays even during high-demand periods. This confirms that combining geometric channelization with evidence-based signal optimization can dramatically enhance intersection performance and sustain acceptable operational conditions under varying traffic volumes.

Environmental and energy efficiency benefits were also observed. Under the Current scenario, CO₂ emissions exceeded 2,100 mg/s and fuel consumption was above 815 mg/s in the morning, rising further during the evening peak. Channelization alone reduced emissions by 10–20%, and optimized signal timings further lowered CO₂ emissions and fuel consumption by 25–35% relative to the baseline. These reductions highlight that improvements in traffic flow directly translate into environmental gains, as smoother vehicle progression reduces idling and stop-and-go operations. The comparative analysis between morning and evening peaks reveals that the evening consistently experiences higher queues, delays, and emissions, a consequence of increased traffic demand. Nevertheless, the optimized scenario maintained robust performance, demonstrating its effectiveness under heavier congestion. This indicates that the integrated approach is not only efficient under typical conditions but also resilient to peak-period stress.

To place the observed improvements in a broader regional context, it is useful to compare the magnitude of delay and queue reductions with those reported in other microsimulation studies conducted under heterogeneous traffic conditions in developing countries. For example, an intersection microsimulation study in Dhaka that combined video data analysis and optimized signal timing reported significant reductions in queue length (around 40 %) and corresponding decreases in delay through data-driven signal adjustments and expert-tuned scenarios. However, the reductions were more moderate than those observed here [22]. In another study from Pakistan, geometric and signal improvements modelled with microsimulation yielded nearly 40 % reduction in delay and fuel consumption, demonstrating substantial performance gains, albeit below the ~70 % delay reduction achieved in this work [6]. Similarly, research on heterogeneous traffic using calibrated simulation in Indian urban settings shows improved intersection performance, though exact quantitative improvements (e.g., in average delay or queue length) tend to vary between 20 % and 60 % depending on local context and modelling assumptions [13], [23]. By comparison, the more than 70% reduction in average delay observed in the present study suggests that the combination of channelization and optimized fixed-time signal control, when applied within a rigorously calibrated SUMO model, delivers performance improvements at the higher end of reported outcomes in similar contexts. In summary, the discussion of queue lengths, delays, emissions, and fuel consumption in conjunction with LOS evaluation demonstrates the multi-dimensional benefits of combining channelization with optimized signal control. While channelization alone provides notable operational improvements, only the combined application achieves a balance of acceptable service levels, reduced environmental impact, and efficient fuel usage. These findings provide strong evidence for urban traffic management strategies that integrate geometric modifications with adaptive signal optimization to enhance both performance and sustainability.

5. Limitations and Future Work

While the results indicate notable operational and environmental improvements from channelization and optimized signal timing, certain limitations should be recognized. Traffic data were collected during peak periods on a single representative weekday; therefore, the results primarily reflect peak-hour conditions and may not fully capture day-to-day, seasonal, or weather-related variability. Incorporating multi-day and multi-season observations would enhance the robustness of future analyses. Although SUMO is well-suited for modeling heterogeneous traffic, some locally prevalent behaviors, such as informal lane usage and non-lane-based movements, can only be approximated through calibration rather than explicitly modeled. Despite satisfactory agreement with observed queues and delays, this may influence the detailed representation of highly irregular traffic interactions. The signal timings were optimized using a fixed-time Webster-based approach, which assumes relatively stable demand within the analysis period. While this method is practical and easy to implement, it does not account for short-term demand fluctuations; future studies could compare

adaptive or real-time control strategies. Finally, the analysis was limited to a single isolated intersection, and corridor-level or network-wide interactions were not considered. Extending the framework to multi-intersection systems would provide broader insights into cumulative traffic performance.

Overall, these limitations do not undermine the validity of the findings but rather highlight opportunities for extending the methodology in future research.

6. Conclusion

Using field data and a calibrated SUMO microsimulation, this study evaluated three scenarios: the current manual police control, channelization with existing timings, and channelization with optimized fixed-time signals to examine intersection performance in Dhaka, a city burdened by chronic congestion and mixed traffic. A key methodological contribution of this research is the rigorous calibration of the SUMO model using the Krauß car-following framework, with locally observed traffic composition and driver-behavior parameters, enabling a realistic representation of Dhaka's heterogeneous, weakly lane-disciplined traffic conditions. The findings clearly demonstrate that while channelization alone alleviates delays and reduces queue lengths, the greatest improvements occur when it is coupled with optimized signal control. Together, these interventions reduced average delays by more than 70%, lowered fuel consumption and CO₂ emissions by up to 35%, and improved the level of service from failing to stable conditions. The reliability of these performance gains is strengthened by the validated calibration process, which ensured close agreement between simulated and observed queue lengths and vehicle delays. Beyond operational efficiency, the results underscore the environmental and energy-saving benefits of integrated traffic management strategies, offering a dual advantage for both mobility and sustainability. For rapidly urbanizing cities like Dhaka, where resources for large-scale infrastructure expansion are limited, low-cost, evidence-based measures such as channelization and optimized signalization offer practical, immediate solutions to congestion. The calibrated SUMO modeling framework developed in this study is transferable and can be applied to other South Asian cities with similar heterogeneous traffic characteristics. Looking ahead, policymakers and urban planners should prioritize adopting data-driven signal control and incremental geometric improvements at critical intersections. Integrating such strategies into a broader smart mobility framework will not only ease congestion but also contribute to cleaner air, reduced fuel dependency, and improved quality of urban life. In doing so, Dhaka can move toward a more resilient, efficient, and sustainable transport future.

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