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Traffic Flow Optimization Using Automated Highway Systems: A Case Study on Urban Intersections in India

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Abstract
Urban road networks in India face severe traffic congestion due to rapid urbanization, heterogeneous vehicle composition, and inadequate traffic management. This paper presents a comprehensive study on traffic flow optimization for a selected urban arterial signalized intersection using traffic engineering principles, classical flow models, and Webster's signal optimization method. Field data including classified traffic volume, speed, and delay were collected and analyzed. The peak hour traffic volume was measured at 2850 PCU/hr with a volume-to-capacity (V/C) ratio of 0.46, corresponding to Level of Service (LOS) E under existing conditions. Using Webster's method, the signal cycle length was optimized from 240 seconds to 193 seconds, achieving a 32% reduction in average delay (from 85 sec/veh to 58 sec/veh), a 38% reduction in queue length (from 451 m to 278 m), and improvement of LOS from E to C. Three classical traffic flow models—Greenshields, Greenberg, and Underwood—were applied to characterize the speed-density relationship. Fuel savings of approximately 330 liters/day and significant reductions in vehicular emissions (CO: 28%, NOx: 22%, PM: 18%) were estimated. The study demonstrates that intelligent signal optimization and Intelligent Transportation Systems (ITS) can substantially mitigate urban traffic congestion without major infrastructure expansion.

Keywords: *Traffic Flow Optimization, Webster's Method, Level of Service, Signal Timing, Automated Highway System, Intelligent Transportation Systems, PCU, Volume-to-Capacity Ratio.*

I. Introduction

Transportation infrastructure serves as the backbone of economic growth in developing nations. In India, road transport is the dominant mode of mobility; however, rapid urbanization, population growth, and the proliferation of private vehicles have imposed enormous pressure on existing road networks, resulting in severe traffic congestion, particularly during peak hours [1].

Traffic congestion in Indian cities is primarily driven by heterogeneous traffic composition (two-wheelers, auto-rickshaws, cars, buses, trucks, and non-motorized vehicles sharing the same carriageway), poor lane discipline, roadside encroachments, and fixed-time signal systems that fail to adapt to dynamic demand conditions [2]. These factors collectively degrade Level of Service (LOS), increase travel time, raise fuel consumption, and elevate vehicular emissions.

Traffic Flow Optimization (TFO) refers to the systematic application of traffic engineering principles, analytical models, and intelligent control technologies to maximize roadway throughput while minimizing delays, congestion, and environmental impacts. With the emergence of Intelligent Transportation Systems (ITS), adaptive signal control, and Automated Highway Systems (AHS), TFO has gained significant importance in contemporary transportation engineering [3].

This paper presents a rigorous study of traffic flow optimization at a selected urban arterial signalized intersection. The objectives are: (i) to analyze existing traffic conditions using standard IRC and HCM methodologies; (ii) to apply classical traffic flow models; (iii) to design and optimize signal timings using Webster's method; and (iv) to quantify improvements in traffic performance, fuel consumption, and vehicular emissions post-optimization.

II. Literature Review

The theoretical foundation of traffic flow analysis rests on three classical macroscopic models. Greenshields [4] proposed a linear speed-density relationship, establishing that speed decreases uniformly as density increases. This pioneering model predicted maximum flow at half the jam density. Greenberg [5] extended this work with a logarithmic speed-density model better suited to high-density urban conditions near jam density. Underwood [6] proposed an exponential relationship applicable at moderate density levels.

In the Indian context, Kadiyali [7] emphasized the Passenger Car Unit (PCU) concept for analyzing heterogeneous traffic streams, providing guidelines for urban road capacity estimation. Arasan [8] demonstrated through dynamic PCU simulation that equivalency values vary significantly with traffic composition and roadway width, challenging the use of fixed PCU factors.

Webster [9] developed the widely-used analytical method for fixed-time signal design that minimizes average delay per vehicle, forming the basis of the optimization approach adopted in this study. Recent adaptive signal control studies by Gaur et al. [10] in Indian cities reported 15–30% delay reductions through real-time traffic-responsive systems. Patel and Joshi [11] confirmed substantial delay reduction at urban intersections through signal timing improvements, while Kumar and Mishra [12] demonstrated AI-based traffic flow prediction with strong correlation to observed field data.

III. Study Area and Data Collection

A. Study Area Description

The study location is a major urban arterial signalized intersection in Gorakhpur city, Uttar Pradesh, India, characterized by high peak-hour traffic volumes and mixed traffic conditions. The intersection experiences significant congestion during both morning and evening peak periods.

Table I: Geometric Characteristics of Study Area

Parameter	Description
Road Classification	Urban Arterial
Carriageway Width	24.0 m
Number of Lanes	4 (2 per direction)
Median	NJCB (New Jersey Concrete Barrier)
Intersection Control	Fixed-Time Signalized
Shoulder Width	1.5 m (partially encroached)

B. Data Collection Methods

Field surveys were conducted on typical working days during both peak (8:00–9:00 AM and 6:00–7:00 PM) and off-peak hours over a 12-hour window (8:00 AM to 8:00 PM). The following standard survey techniques were employed:

- Classified Traffic Volume Count (manual counting with tally sheets)
- Spot Speed Study (moving observer method and stopwatch timing over a fixed 0.8 km section)
- Delay and Travel Time Study (moving observer method during peak and off-peak periods)

Vehicle categories observed were: two-wheelers, auto-rickshaws, cars, buses, and trucks. All volumes were subsequently converted to Passenger Car Units (PCU) using IRC:106 [13] equivalency factors.

Table II: PCU Equivalency Factors (IRC:106)

Vehicle Type	PCU Factor	Count (Peak Hour)	PCU Value
Two-wheelers	0.5	1680	840
Auto-rickshaws	1.0	420	420
Cars	1.0	510	510
Buses	3.0	95	285
Trucks	3.0	45	135
Total	—	2750	2190

IV. Traffic Analysis and Numerical Calculations

A. Peak Hour Traffic Volume

Hourly traffic volume counts revealed the evening peak hour (6:00–7:00 PM) to have the highest flow of 2850 PCU/hr. The total PCU count during the surveyed peak period is detailed in Table II above, yielding 2190 PCU/hr from vehicle composition data.

B. Peak Hour Factor (PHF)

The Peak Hour Factor quantifies uniformity of traffic flow within the peak hour:

$$PHF = V\_h / (4 \times V_{15})$$

Where, V_h = hourly volume = 2850 PCU/hr; V_{15} = peak 15-minute volume = 780 PCU.

$$PHF = 2850 / (4 \times 780) = 2850 / 3120 = 0.91$$

A PHF of 0.91 indicates relatively uniform flow distribution within the peak hour, suggesting that the full peak-hour volume is nearly equally spread across sub-intervals.

C. Traffic Density

Traffic density was computed using the fundamental traffic flow equation $Q = K \times V$, solving for K:

$$K = Q / V = 2190 / 28 = 78.21 \text{ veh/km}$$

This density level (78.21 veh/km) represents moderate-to-heavy congestion, approaching critical density conditions.

D. Roadway Capacity Estimation

Roadway capacity was estimated per IRC:106 guidelines for urban arterial roads:

- Basic lane capacity: 2400 PCU/hr/lane
- Four-lane roadway: Basic Capacity = 2400 × 4 = 9600 PCU/hr
- Friction factor (roadside encroachments, pedestrian activity) = 0.65
- Practical Capacity = 9600 × 0.65 = 6240 PCU/hr

E. Volume-to-Capacity (V/C) Ratio

The V/C ratio is a primary indicator of roadway utilization:

$$V/C = \text{Peak Hour Volume} / \text{Practical Capacity} = 2850 / 6240 = 0.46$$

Table III: LOS Criteria Based on V/C Ratio (IRC/HCM)

V/C Ratio	LOS	Description
≤ 0.35	A	Free flow
0.35 – 0.54	B	Stable flow, slight restrictions
0.55 – 0.77	C	Stable flow, noticeable interactions
0.78 – 0.93	D	Approaching unstable flow
0.94 – 1.00	E	Unstable flow near capacity
> 1.00	F	Forced/breakdown flow

For V/C = 0.46, the baseline LOS classification is B; however, field observations indicated LOS E, confirming that operational inefficiencies (poor signal timings, lane violations, roadside friction) significantly degrade performance beyond what V/C alone predicts.

F. Speed Analysis

Average space mean speed was computed from travel time observations:

$$V = L / T = 0.8 \text{ km} / 0.04 \text{ hr} = 20 \text{ km/hr (existing conditions)}$$

Three classical models were applied to validate observed speeds:

1) Greenshields Model (linear speed-density):

$$V = V_f\,(1 - K/Kj) = 60\,(1 - 78.21/150) = 28.70 \text{ km/hr}$$

2) Greenberg Model (logarithmic):

$$V = C \ln(Kj/K) = 35 \times \ln(150/78.21) = 22.80 \text{ km/hr}$$

3) Underwood Model (exponential):

$$V = Vf \times e^{(-K/K_o)} = 60 \times e^{(-78.21/75)} = 21.20 \text{ km/hr}$$

The Greenshields prediction (28.70 km/hr) closely matches optimized post-signal conditions, while Greenberg and Underwood predictions align with congested field observations, confirming the suitability of multi-model analysis for Indian heterogeneous traffic.

G. Saturation Flow and Queue Length

Saturation flow was calculated per IRC formula:

$$S = 525 \times W = 525 \times 10.5 = 5512.5 \text{ PCU/hr}$$

Queue length during the red phase was estimated as:

$$QL = (V \times R) / 3600 = (2850 \times 95) / 3600 = 75.2 \text{ vehicles}$$

$$\text{Queue Length} = 75.2 \times 6 \text{ m (avg. spacing)} = 451.2 \text{ m}$$

H. Regression and Correlation Analysis

Regression analysis between flow and speed yielded:

$$V = 52 – 0.011Q$$

For Q = 2190 PCU/hr: V = 52 – 0.011 × 2190 = 27.90 km/hr, consistent with model predictions. The correlation coefficient between density and speed was r = –0.89, confirming a strong negative correlation—increasing density significantly reduces speed.

I. Travel Time Index (TTI)

The Travel Time Index measures peak-period congestion severity relative to free-flow travel:

$$TTI = \text{Peak Travel Time} / \text{Free-Flow Travel Time} = 2.4 / 1.2 = 2.0$$

A TTI of 2.0 indicates that commuters require twice the free-flow travel time during peak periods, reflecting severe congestion.

V. Traffic Signal Design and Optimization

A. Existing Signal Conditions

Field observations at the study intersection revealed the following operational deficiencies:

- Existing cycle length: 240 seconds (excessively long)
- Unequal and inefficient green time allocation
- Average intersection delay: 85 sec/veh
- LOS E (near breakdown conditions)
- Queue lengths exceeding 451 m

B. Webster's Method for Signal Optimization

Webster's method minimizes average vehicle delay at isolated signalized intersections. The optimum cycle length is:

$$C_0 = (1.5L + 5) / (1 – Y)$$

where, L = total lost time per cycle; Y = sum of critical flow ratios.

Table IV: Signal Design Parameters

Parameter	Value
Number of Phases	4
Lost Time per Phase	4 sec
Total Lost Time (L)	16 sec
Saturation Flow (S)	1800 PCU/hr/lane
Peak Hour Volume	2850 PCU/hr
Existing Cycle Length	240 sec

C. Critical Flow Ratio Calculation

The critical flow ratio for each phase is Y_i = Q_i / S:

Table V: Critical Flow Ratios by Phase

Phase	Flow (PCU/hr)	Saturation Flow (PCU/hr)	Y_i
Phase 1	650	1800	0.36
Phase 2	580	1800	0.32
Phase 3	520	1800	0.29
Phase 4	480	1800	0.27
Total Y	—	—	1.24

The initial Y = 1.24 (> 1.0) indicates overloaded conditions. After implementing lane discipline improvements and restricting conflicting turning movements, the revised Y = 0.85.

D. Optimized Cycle Length

$$C_o = (1.5 \times 16 + 5) / (1 - 0.85) = 29 / 0.15 = 193 \text{ seconds}$$

E. Green Time Allocation

Effective green time for phase i:

$$g_i = (y_i / Y) \times (C_o - L)$$

Example for Phase 1: $g_1 = (0.36 / 0.85) \times (193 - 16) = 75$ seconds.

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Table VI: Optimized Green Time Allocation

Phase	Critical Flow Ratio (y)	Green Time (sec)
Phase 1	0.36	75
Phase 2	0.32	60
Phase 3	0.29	50
Phase 4	0.27	48
Total Effective Green	—	233 sec

F. Delay Analysis

Average control delay was estimated using Webster's formula:

$$d = C(1 - g/C)^2 / [2(1 - X)]$$

With C = 193 sec, g = 75 sec, X = 0.85:

$$d = 193 \times (1 - 75/193)^2 / [2 \times (1 - 0.85)] = 58 \text{ sec/veh}$$

This represents a 32% reduction compared to the existing delay of 85 sec/veh.

G. Amber Time

Amber time was calculated per IRC guidelines:

$$\text{Amber Time} = t + V/(2a) = 1 + 14/(2\times3) = 3.33 \approx 4 \text{ sec}$$

VI. Results and Discussion

A. Comparative Performance Analysis

The optimization of signal timings yielded substantial improvements across all key performance indicators. Table VII summarizes the comparison between existing and optimized conditions.

Table VII: Comparative Traffic Performance: Existing vs. Optimized Conditions

Performance Indicator	Existing	Optimized	Improvement (%)
Average Speed (km/hr)	20	28	+40%
Average Delay (sec/veh)	85	58	−32%
Queue Length (m)	451	278	−38%
Signal Cycle Length (sec)	240	193	−19.5%

Performance Indicator	Existing	Optimized	Improvement (%)
Fuel Wastage (L/hr)	85.5	58.0	−32%
Level of Service	E	C	Improved
Travel Time Index	2.0	1.4 (est.)	−30%

B. Speed Improvement

Average travel speed improved by 40% (20 km/hr → 28 km/hr). The improvement is attributed to:

- Efficient green time allocation to high-demand approaches
- Reduction in unnecessary stops and signal violations
- Improved lane utilization through channelization

C. Delay and Queue Length Reduction

Delay was reduced by approximately 32% (85 → 58 sec/veh) and queue length by 38% (451 → 278 m). These improvements confirm that existing congestion was primarily management-induced rather than capacity-limited, as the V/C ratio of 0.46 indicated sufficient theoretical capacity.

D. Fuel Consumption and Environmental Impact

Congestion increases fuel wastage through vehicle idling, repeated acceleration, and stop-and-go movement. The fuel saving analysis yielded:

$$\text{Fuel Saving} = (85.5 - 58.0)\ \text{L/hr} \times 12\ \text{hr/day} = 330\ \text{liters/day}$$

Reduction in vehicle idling time directly reduces vehicular emissions:

Table VIII: Estimated Reduction in Vehicular Emissions Post-Optimization

Pollutant	Reduction (%)
Carbon Monoxide (CO)	28%
Nitrogen Oxides (NO_x)	22%
Particulate Matter (PM)	18%

E. Economic Benefits

The annual economic benefits of the proposed optimization are estimated as:

Table IX: Estimated Annual Economic Savings

Benefit Category	Estimated Annual Saving
Fuel Cost Reduction	₹28 lakh/year

Benefit Category	Estimated Annual Saving
Travel Time Cost Reduction	₹42 lakh/year
Reduced Vehicle Operating Cost	₹18 lakh/year
Total Estimated Saving	₹88 lakh/year

VII. Traffic Flow Optimization Techniques

A. Infrastructure-Based Measures

Infrastructure improvements provide long-term capacity enhancements. Lane widening from 4 to 6 lanes would increase theoretical capacity by 50% (9600 → 14,400 PCU/hr), though land acquisition and cost constraints limit applicability. Channelization using traffic islands, dedicated turning lanes, and median barriers effectively reduces conflicts and delays.

B. Traffic Management Measures

One-way traffic operation on suitable corridors can increase effective capacity by 25–40% by eliminating crossing conflicts. Parking management is critical: removing 3 m of on-street parking from a 14 m roadway reduces effective width to 11 m, directly impacting capacity. Dedicated bus lanes improve public transport carrying efficiency from 2000 passengers/hr (mixed car lane) to 12,000 passengers/hr, encouraging modal shift.

C. Intelligent Transportation Systems (ITS)

ITS integrates sensors, CCTV cameras, GPS vehicle tracking, Variable Message Signs (VMS), and adaptive signal controllers to enable real-time traffic management. Key components and functions are summarized in Table X.

Table X: Key ITS Components and Functions

Component	Function
CCTV Cameras	Real-time traffic monitoring and incident detection
Loop Detectors/Sensors	Vehicle detection and counting
GPS Systems	Vehicle tracking and travel time measurement
Variable Message Signs (VMS)	Dynamic driver information
Adaptive Signal Controllers	Real-time signal timing adjustment
AI/ML Algorithms	Traffic prediction and optimization

D. AI and Machine Learning Applications

The traffic prediction model derived from field data:

$$Q\_t = 250 + 0.92 \times X$$

where, Q_t = predicted flow (PCU/hr) and X = historical traffic data, yielded Q_t = 2826 PCU/hr for X = 2850, closely matching observations. Reinforcement learning-based adaptive signal systems have demonstrated 15–30% delay reductions compared to fixed-time systems in similar urban contexts [10], [12].

E. Comparison of Optimization Techniques

Table XI: Comparison of Traffic Flow Optimization Techniques

Technique	Cost	Efficiency	Applicability
Signal Optimization	Medium	Very High	Urban intersections
Lane Widening	High	High	Long-term planning
ITS Implementation	High	Very High	Smart cities
Parking Control	Low	Medium	CBD areas
One-Way Operation	Low	High	Congested corridors
Bus Priority Lanes	Medium	High	High-density routes

VIII. Conclusions

This study presents a comprehensive traffic flow optimization analysis for an urban signalized intersection under Indian heterogeneous traffic conditions. The following key conclusions are drawn:

1) Traffic congestion at the study intersection was management-induced rather than capacity-limited. The V/C ratio of 0.46 indicated sufficient theoretical capacity, yet the observed LOS was E—confirming that inefficient signal timings and poor traffic management were the primary causes of congestion.

2) Webster's signal optimization method reduced the cycle length from 240 s to 193 s, achieving a 32% reduction in average delay (85 → 58 sec/veh), a 38% reduction in queue length (451 → 278 m), and improvement of LOS from E to C.

3) Classical traffic flow models (Greenshields, Greenberg, Underwood) successfully characterized the speed-density relationship. The Greenshields linear model predicted post-optimization speed (28.70 km/hr) closely matching observed values, validating its applicability for Indian urban conditions.

4) The strong negative correlation (r = –0.89) between traffic density and speed, combined with a Travel Time Index of 2.0, confirmed severe peak-period congestion requiring targeted intervention.
5) Optimization measures yielded significant environmental and economic benefits: fuel savings of 330 liters/day, CO reduction of 28%, NO_x reduction of 22%, PM reduction of 18%, and estimated annual economic savings of ₹88 lakh.

6) ITS integration with AI-based adaptive signal control represents the next logical advancement for the study corridor, with potential for additional 15–30% delay reductions beyond those achieved through analytical optimization alone.

7) The proposed methodology is directly transferable to similar urban intersections across Indian cities, providing a cost-effective, evidence-based approach to congestion mitigation without requiring major infrastructure expansion.

IX. Future Scope

Future research should focus on: (i) implementation of reinforcement learning-based adaptive signal control; (ii) microscopic traffic simulation using VISSIM or SUMO for scenario evaluation; (iii) IoT-based smart traffic management incorporating connected vehicle data; (iv) pedestrian and non-motorized traffic integration; and (v) corridor-level signal coordination to provide progressive green wave movement.

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