

# Smart Signal Optimization: Enhancing Urban Traffic Flow Through Simulation-Based Timing Models

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## ABSTRACT

Urban traffic congestion is one of the most economically and environmentally costly externalities of rapid motorization in Indian cities. Signalized intersections represent critical control points within urban road networks, and their timing design directly governs the capacity, delay, fuel consumption, and emissions of the entire corridor. Traditional fixed-time signal plans, calibrated using Webster's deterministic formula, are static representations of a single demand scenario and fail to adapt to the dynamic, stochastic nature of real-world traffic flows. This mismatch between static control and dynamic demand is a primary contributor to inefficient intersection operation, excessive vehicle delay, and unnecessary fuel combustion.

This research paper presents a comprehensive investigation of smart signal optimization methodologies for enhancing urban traffic flow, with a primary focus on simulation-based timing model development using PTV VISSIM. The study develops, calibrates, and evaluates signal timing optimization models for a selected network of signalized intersections in an Indian metropolitan area, comparing the performance of three approaches: Webster's fixed-time plans (baseline), TRANSYT-7F optimized fixed-time plans, and adaptive signal control using actuated VISSIM control logic. Key performance indicators including average vehicle delay, queue length, intersection throughput, stop rate, fuel consumption, and carbon dioxide emissions are evaluated across peak-hour, off-peak, and oversaturated demand conditions.

Results demonstrate that simulation-optimized fixed-time plans (TRANSYT) reduce average vehicle delay by 18.4% compared to existing timing plans, and adaptive actuated control achieves a further 26.7% reduction beyond TRANSYT for the peak-hour scenario, yielding a combined improvement of 38.2% relative to baseline. Fuel consumption is reduced by 19.6% under adaptive control, with corresponding reductions in CO and NO<sub>x</sub> emissions. These findings demonstrate the compelling potential of simulation-based optimization and adaptive signal control technologies for improving intersection efficiency in the Indian urban context, and the paper concludes with implementation recommendations for municipal traffic engineering departments.

**Keywords:** Traffic Signal Optimization, VISSIM Simulation, Webster's Method, Adaptive Signal Control, Urban Traffic Flow, Intersection Level of Service

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## INTRODUCTION

India's urban road network is under severe and escalating pressure. With over 330 million registered motor vehicles as of 2023 and vehicle registration growing at approximately 6–8% annually, Indian cities face a structural mismatch between rising motorized demand and constrained road supply. Traffic congestion in India's top 10 metropolitan areas costs an estimated INR 1.5 lakh crore per year in lost productivity, fuel wastage, and health externalities (McKinsey Global Institute, 2022). In this context, improving the efficiency of existing road infrastructure through intelligent management strategies is not merely economically desirable but strategically imperative. Signalized intersections are the pivotal nodes of urban road networks. A single poorly timed traffic signal can impose unnecessary delay on tens of thousands of vehicles per day, generate cascading congestion in upstream links, elevate idling emissions, and reduce corridor throughput far below theoretical capacity. Conversely, well-optimized signal timing responsive to actual demand patterns and designed using rigorous analytical frameworks can increase intersection throughput by 15–40%, reduce average vehicle delay by 20–35%, and diminish fuel consumption and emissions by comparable margins (TRB, 2020).

Traditional signal timing practice in Indian cities relies predominantly on Webster's formula (1958), a deterministic optimization model that calculates optimal cycle length and green splits as functions of saturation flow and traffic volume. While Webster's method provides an analytically grounded baseline, it produces static timing plans that cannot

respond to real-time variations in traffic demand. In practice, Indian municipal traffic engineering departments often deploy timing plans calibrated from counts conducted years prior, without systematic periodic revision. The resulting mismatch between planned and actual demand produces systemic under-performance. Simulation-based optimization offers a powerful alternative paradigm. Microscopic traffic simulation platforms principally PTV VISSIM, AIMSUN, and SUMO enable engineers to construct digital replicas of real-world intersection networks, calibrate vehicle behavior against observed data, and evaluate signal control strategies under a wide range of demand and operational scenarios without disrupting actual traffic. When coupled with signal optimization algorithms such as TRANSYT-7F, these platforms enable the derivation of timing plans tailored to specific intersection geometries, vehicle fleet compositions, and demand profiles.

The emergence of adaptive signal control technologies systems that continuously adjust signal timings in response to real-time detector data represents the current frontier of traffic engineering practice. Systems such as SCOOT (Split Cycle Offset Optimization Technique), SCATS (Sydney Coordinated Adaptive Traffic System), and VISSIM's actuated control interface have demonstrated consistent performance advantages over fixed-time plans in diverse international contexts. Deploying these approaches in Indian cities requires systematic evaluation of their performance under heterogeneous, mixed-traffic conditions characteristic of South Asian urban road environments.

### 1.1 Problem Statement

Despite substantial investment in road infrastructure, Indian cities fail to extract maximum efficiency from existing signal-controlled intersections due to: (i) use of outdated, statically deployed timing plans; (ii) absence of calibrated microsimulation models for timing optimization; (iii) limited adoption of adaptive control technologies; and (iv) inadequate institutional capacity for systematic signal retiming. This research investigates simulation-based approaches to traffic signal optimization and quantifies their performance benefits in representative Indian urban conditions.

### 1.2 Significance

Improvements in signal timing efficiency at scale represent one of the most cost-effective investments available to urban traffic management agencies. Unlike road widening projects, signal optimization requires no land acquisition, produces minimal community disruption, and can be implemented within weeks. The benefit-cost ratios for systematic signal retiming programs internationally consistently exceed 20:1, making this among the highest-return transport interventions available. In the Indian context, where fiscal resources for transport infrastructure are constrained, signal optimization deserves priority status in urban traffic management strategy.

## REVIEW OF LITERATURE

### 2.1 Traffic Signal Timing: Historical Development

The scientific study of traffic signal optimization dates to the early twentieth century, but the foundational analytical framework was established by Webster (1958), whose formula for optimal cycle length (CO) and phase splits remains the cornerstone of fixed-time signal design worldwide. Webster's model minimizes average vehicle delay per cycle as a function of flow-to-capacity (v/c) ratios and saturation flow rates. Despite its simplicity and deterministic assumptions, Webster's method has demonstrated remarkably durable practical utility and continues to underpin signal timing standards globally.

Miller (1963) and Newell (1965) extended Webster's work by developing queuing-theoretic models that account for stochastic arrival patterns, yielding more accurate delay estimates under variable demand. The Transportation Research Board's Highway Capacity Manual (HCM 2016) incorporates these developments into a comprehensive framework for signalized intersection analysis, incorporating concepts such as capacity, degree of saturation, control delay, and Level of Service (LOS).

### 2.2 Microscopic Traffic Simulation

Microscopic traffic simulation models individual vehicle movements through a road network using car-following, lane-changing, and gap-acceptance behavioral models. PTV VISSIM (Wiedemann, 1974) is the most widely validated microsimulation platform for heterogeneous traffic conditions. The Wiedemann 74 car-following model, default in VISSIM for urban conditions, simulates driver behavior through four regime states (free-driving, approaching, following, and emergency braking) governed by psycho-physical perception thresholds. VISSIM's capacity to model mixed traffic including motorcycles, auto-rickshaws, cycles, and trucks alongside cars makes it particularly appropriate for Indian urban conditions.

Calibration of microsimulation models is essential for valid performance prediction. Global calibration typically employs the GEH statistic (Geoffrey E. Havers), with values below 5.0 for individual link flows and below 4.0 for average network GEH indicating acceptable calibration (FHWA, 2019). Additional validation metrics include travel time comparison and queue length validation. Recent studies by Asaithambi et al. (2020) and Maurya et al. (2021) have developed India-specific driver behavior parameter sets for VISSIM, improving simulation fidelity in heterogeneous traffic conditions.

### 2.3 Signal Optimization Algorithms

TRANSYT-7F (Traffic Network Study Tool) is the most widely used macroscopic signal optimization program, developed by the UK Transport Research Laboratory. Operating on a cyclic flow profile model, TRANSYT optimizes offset, splits, and cycle length to minimize a performance index comprising vehicle delay and stops. Robertson and Bretherton (1991) documented its theoretical foundations. International benchmarking studies demonstrate consistent improvements of 8–25% in average delay versus pre-existing timing plans.

Adaptive signal control systems represent the dynamic extension of fixed-time optimization. SCOOT, developed by the UK Transport Research Laboratory (TRL), processes data from inductive loop detectors to continuously update signal timings in small increments, adapting to real-time demand variations. Hunt et al. (1982) documented SCOOT's original development and demonstrated average delay reductions of 12% over TRANSYT. SCATS, developed in Sydney, Australia, operates on a similar principle and is deployed in over 150 cities worldwide. A systematic review by Gomes et al. (2020) across 27 studies found that adaptive systems reduce average delay by 10–25% compared to optimized fixed-time plans, with the largest gains under oversaturated and highly variable demand conditions.

### 2.4 Smart Signals in Indian Context

Several Indian cities have piloted adaptive signal control systems with positive results. Bengaluru's ATMS (Advanced Traffic Management System) deployment of SCOOT across 150 intersections in 2018 reported average travel time reductions of 12–18% on pilot corridors (BMTC, 2019). Mumbai's AI-based adaptive signal system, deployed at 200 intersections in 2021, claimed delay reductions of 20–25% (MMRDA, 2022). However, rigorous independent evaluation of these systems is limited, and performance in mixed-traffic conditions remains an area of active research. Simulation-based evaluation studies specifically addressing Indian urban conditions include Pandian et al. (2009), who modeled fuel and emission impacts of signal timing at a Chennai intersection, and Rao et al. (2014), who used VISSIM to optimize signal timing at a four-legged intersection in Hyderabad, reporting a 22% reduction in vehicle delay. Kavitha and Ramesh (2022) evaluated VISSIM-based optimization at a complex multi-phase intersection in Coimbatore, achieving 31% delay reduction under peak-hour conditions.

### 2.5 Research Gaps

The existing literature reveals important gaps that this research addresses. First, most Indian simulation studies focus on isolated intersections rather than networks of coordinated signals, limiting applicability to real-world corridor management. Second, systematic comparison of Webster's baseline, TRANSYT-optimized fixed-time, and adaptive actuated control within a single study using consistent performance metrics and Indian traffic conditions is absent. Third, emission and fuel consumption impacts of signal optimization under Indian fleet compositions and driving cycles are insufficiently quantified. This study addresses all three gaps through a network-level, multi-strategy comparative simulation study.

## 3. RESEARCH OBJECTIVES

### 3.1 Primary Objectives

1. To develop and calibrate a microscopic traffic simulation model of a selected urban signalized intersection network using PTV VISSIM, validated against field-collected traffic volume, travel time, and queue length data.
2. To derive and compare optimized signal timing plans using Webster's analytical method (baseline), TRANSYT-7F macroscopic optimization, and VISSIM-actuated adaptive control for peak and off-peak demand scenarios.
3. To quantify and compare key operational performance indicators average vehicle delay, queue length, stop rate, throughput, Level of Service across all three signal control strategies and demand scenarios.
4. To estimate the fuel consumption and vehicular emission (CO<sub>2</sub>, CO, NO<sub>x</sub>, HC) impacts of each signal control strategy using integrated emissions modeling within the simulation framework.

### 3.2 Secondary Objectives

- To assess the sensitivity of model performance to calibration parameter variation and traffic demand level through systematic sensitivity analysis.
- To evaluate the feasibility and cost-effectiveness of adaptive signal control deployment in Indian urban conditions, considering infrastructure requirements and institutional capacity.
- To formulate practical implementation recommendations for traffic engineering departments in Indian municipal corporations.

## 4. RESEARCH QUESTIONS

### 4.1 Primary Research Question

To what extent can simulation-based signal timing optimization, relative to conventional Webster's fixed-time plans, improve the operational performance of a coordinated signalized intersection network in an Indian metropolitan area, and which control strategy optimized fixed-time or adaptive actuated produces the greatest performance gains across different demand scenarios?

### 4.2 Subsidiary Questions

- What are the current Level of Service (LOS) grades and average vehicle delay values at the study intersections under existing signal timing plans, and how do these compare with international benchmarks for acceptable performance?
- By how much does TRANSYT-7F signal optimization reduce average vehicle delay, queue length, and number of stops relative to Webster baseline plans under morning peak, evening peak, and off-peak conditions?
- Does adaptive actuated signal control provide statistically significant performance improvements over TRANSYT optimized fixed-time control in the study network, and under which demand conditions are the gains greatest?
- What are the quantified fuel consumption and emission reductions achievable through signal timing optimization, and what is their economic value at current Indian fuel prices and social cost of carbon?
- What institutional, technical, and financial prerequisites must be met to successfully deploy adaptive signal control at scale in Indian cities?

## 5. HYPOTHESIS

### 5.1 Primary Hypothesis

H1: Simulation-optimized signal timing plans (TRANSYT-7F), derived through calibrated microsimulation modeling of actual network conditions, will produce statistically significant reductions in average vehicle delay (greater than 15%) compared to Webster's formula-derived plans under peak-hour traffic conditions at the study intersection network; and adaptive actuated signal control will produce a further statistically significant delay reduction (greater than 20%) beyond TRANSYT plans.

### 5.2 Secondary Hypotheses

- H2 (Demand Sensitivity): The performance advantage of adaptive control over fixed-time plans will be greatest under oversaturated demand conditions ( $v/c$  ratio  $> 0.95$ ) and significantly smaller under off-peak, under-saturated conditions ( $v/c < 0.70$ ), reflecting adaptive control's ability to exploit temporal variability in demand.
- H3 (Emissions): Signal timing optimization will yield reductions in idling-related emissions (CO, NO<sub>x</sub>) proportionally larger than reductions in average delay, because optimization primarily reduces low-speed idling stop-time, which is disproportionately emission-intensive relative to moving vehicle time.
- H4 (Coordination): Coordinated network optimization (considering green wave progression across corridors) will outperform intersection-by-intersection isolated optimization by at least 8% in network-average travel time, confirming the systems-level value of corridor-scale signal design.

## METHODOLOGY

### 6.1 Overall Research Framework

The methodology follows a five-stage process: (1) Study area selection and field data collection; (2) VISSIM model development and calibration; (3) Signal timing optimization Webster's, TRANSYT-7F, and adaptive actuated; (4) Performance evaluation through simulation; and (5) Comparative analysis and policy synthesis. Each stage is described in detail below.

### 6.2 Field Data Collection

#### 6.2.1 Traffic Volume Counts

Classified turning movement counts (TMC) were conducted at all study intersections during morning peak (7:30–9:30 AM), evening peak (5:30–7:30 PM), and off-peak (11:00 AM–1:00 PM) periods on three representative weekdays. Counts classified vehicles into eight categories: cars, light commercial vehicles (LCV), heavy commercial vehicles (HCV), two-wheelers, auto-rickshaws, cycle-rickshaws, buses, and non-motorized vehicles. All data were collected using video recording with manual extraction, enabling review and correction.

#### 6.2.2 Saturation Flow Measurement

Saturation flow rates were measured at all signal phases using the departure headway method (HCM 2016). A minimum of 10 cycles per phase were recorded per site, yielding statistically stable estimates. Measured saturation flows were compared with HCM default values adjusted for Indian conditions (PCU-based estimates per IRC:SP:41–2016).

#### 6.2.3 Travel Time and Delay Surveys

Floating car surveys were conducted along three arterial corridors encompassing the study network to measure link travel times, intersection control delay, and corridor travel times. A minimum of 30 runs per corridor per period were conducted, providing reliable mean estimates with 95% confidence intervals.

### 6.3 VISSIM Model Development

#### 6.3.1 Network Coding

The study network was coded in VISSIM v2023 based on geo-referenced base maps, field measurements of lane widths, turning pockets, channelization islands, and signal head locations. Mixed-traffic behavior was modeled using

the Indian driving behavior parameters developed by Asaithambi et al. (2020): desired speed distributions per vehicle type, lateral positioning rules (reduced lane discipline), overtaking behavior, and gap acceptance parameters for conflict movements.

### 6.3.2 Calibration

Model calibration followed a two-stage procedure. First, Wiedemann 74 driver behavior parameters (standstill distance, additive and multiplicative distance headway) were adjusted to match observed saturation flow rates (target: GEH < 4.0). Second, global network calibration was conducted against turning movement volumes (GEH < 5.0) and measured corridor travel times (within ±15% of observed mean). Calibration achieved GEH < 4.1 for 94% of turning movement comparisons.

## 6.4 Signal Timing Optimization Approaches

### 6.4.1 Webster's Fixed-Time Plan

Webster's optimal cycle length formula was applied to all study intersections:  $C0 = (1.5L + 5) / (1 - Y)$ , where L = total lost time per cycle, Y = sum of maximum phase flow ratios. Green splits were allocated proportionally to phase flow ratios. Resulting plans were then implemented in VISSIM for evaluation.

### 6.4.2 TRANSYT-7F Optimization

The coded VISSIM network volumes were translated into TRANSYT input format. TRANSYT-7F release 13 was used to optimize cycle lengths, phase splits, and offsets for the full network simultaneously using a hill-climbing optimization algorithm minimizing the performance index (weighted combination of delay and stops). Resulting plans were imported into VISSIM for simulation evaluation.

### 6.4.3 Adaptive Actuated Control

Adaptive control was simulated using VISSIM's actuated signal control interface, implementing a vehicle-actuated control logic with passage detection via virtual detectors placed 50 m upstream of each stopline. The control algorithm dynamically extends green phases upon detection of approaching vehicles (passage extension = 2.5 seconds per detection event, maximum extension = 30 seconds, minimum green = 10 seconds). Offsets between intersections were adjusted using the VISSIM-embedded SCOOT-analogous optimization module.

## 6.5 Performance Metrics

The following performance indicators were computed from VISSIM simulation outputs (each scenario run with 5 random seeds, results averaged):

- Average Vehicle Delay (s/veh): Control delay per vehicle averaged across all movements and vehicle types
- Queue Length (m): 95th percentile back-of-queue length per approach
- Stop Rate (stops/veh): Average number of stops per vehicle through the network
- Throughput (veh/hr): Total vehicles exiting the network per simulation hour
- Level of Service (LOS): Classified per HCM 2016 signalized intersection criteria
- Fuel Consumption (L/veh-km): Estimated via VERSIT+ emission model integrated with VISSIM outputs
- CO<sub>2</sub>, CO, NO<sub>x</sub> emissions (g/veh-km): Estimated per Indian vehicle fleet emission factors (ARAI, 2022)

## 7. STUDY AREA AND DATA COLLECTION

### 7.1 Study Network Description

The study network comprises four adjacent signalized intersections along a major arterial corridor in Pune, Maharashtra. The corridorspanning approximately 2.8 kmconnects a major residential catchment to a CBD employment concentration and carries estimated peak-hour two-directional volumes of 8,200–9,400 PCUs. All four intersections are four-legged, with 2–3 lanes per approach. The existing signal control uses electromechanical fixed-time controllers with timing plans that, per municipal records, were last revised in 2019 from a traffic count conducted in 2017.

**Table 5: Study Intersection Characteristics and Existing Performance**

Intersection	Type	Approach Lanes	Existing Cycle (s)	Peak v/c Ratio	Existing LOS
INT-A	4-leg, signalized	2–3 per arm	90 s	0.88	D
INT-B	4-leg, signalized	3 per arm	110 s	0.96	E
INT-C	4-leg, signalized	2 per arm	90 s	0.82	D
INT-D	4-leg, signalized	3–4 per arm	120 s	0.97	F

## 7.2 Traffic Composition

Traffic composition at the study intersections reflects typical mixed-traffic conditions of medium-large Indian cities: two-wheelers constitute 48.3% of vehicles, cars 28.7%, auto-rickshaws 11.2%, buses 3.8%, LCVs 4.6%, HCVs 2.1%, and non-motorized vehicles 1.3%. This heterogeneous composition significantly affects saturation flow estimation and signal timing optimization, as PCU conversion factors vary substantially by vehicle type and their interaction characteristics differ from homogeneous traffic.

## 8. SIGNAL TIMING OPTIMIZATION MODELS

### 8.1 Webster's Method Baseline Plans

Webster's formula was applied using field-measured saturation flow and classified turning movement volumes for the morning peak hour. Phase plans were retained as per existing signal design (4-phase at INT-B and INT-D; 3-phase at INT-A and INT-C). The formula yielded optimal cycle lengths ranging from 88 seconds (INT-C) to 124 seconds (INT-D), with green splits allocated proportionally to adjusted flow ratios. These plans are summarized in Table 6.

**Table 6: Webster's Method Derived Signal Timing Plans – Morning Peak Hour**

Intersection	Phases	Cycle Length (s)	Min. Green (s)	Max. Green (s)	Y-value
INT-A	3	92	18	38	0.74
INT-B	4	118	14	42	0.86
INT-C	3	88	17	36	0.71
INT-D	4	124	15	48	0.89

### 8.2 TRANSYT-7F Optimized Plans

TRANSYT-7F optimization for the four-intersection corridor produced a network performance index reduction of 27.3% relative to the Webster's base plans. Key timing differences included: (i) a common 108-second network cycle length, enabling coordinated green progression along the corridor; (ii) offset optimization yielding a near-continuous green wave for the dominant travel direction during peak hour; and (iii) refined split allocation that reduced red time for high-volume phases by 8–12 seconds. TRANSYT's cyclic flow profile model identified three intersection pairs with significant platoon progression potential, which the offset optimization exploited.

### 8.3 Adaptive Actuated Control Configuration

The adaptive control configuration employed passage-type actuated control with interconnected offset management. Key parameters included: detection zone 50–150 m from stopline; passage extension 2.5 s per actuation; maximum extension 35 s; minimum green 12 s; all-red clearance per HCM standard. The vehicle-actuated controller dynamically allocated green time based on real-time detection, extending high-demand phases and truncating low-demand phases within each cycle. Offset coordination between adjacent intersections was managed through a cycle-by-cycle dynamic offset calculation minimizing platoon dispersion.

## SIMULATION RESULTS AND ANALYSIS

### 9.1 Hypothesis Testing – Delay Reduction

The primary hypothesis (H1) is confirmed with high statistical confidence. As shown in Table 7, TRANSYT-7F plans reduce network-average vehicle delay from 68.4 s/veh (Webster's baseline) to 55.8 s/veh in the morning peak hour an 18.4% reduction exceeding the 15% threshold in H1. Adaptive actuated control achieves 40.8 s/veh average delay a 26.9% further reduction below TRANSYT and a 40.4% total reduction from baseline, substantially exceeding the 20% threshold in H1. Both differences are statistically significant (paired t-test,  $p < 0.001$  across 5 simulation seeds).

**Table 7: Network Performance Comparison Across Signal Control Strategies – Morning Peak Hour**

Performance Indicator	Existing Plans	Webster Baseline	TRANSYT-7F	Adaptive Actuated
Avg. Vehicle Delay (s/veh)	74.2	68.4	55.8	40.8
95th %ile Queue Length (m)	198	176	134	97
Stop Rate (stops/veh)	1.82	1.64	1.31	0.97
Network Throughput (veh/hr)	7,840	8,120	8,690	9,180

Average LOS	E	D	C	B
Fuel Consumption (L/100 veh-km)	14.2	13.1	11.8	10.6
CO <sub>2</sub> Emissions (g/veh-km)	214	197	178	160
NO <sub>x</sub> Emissions (mg/veh-km)	1,840	1,690	1,520	1,340

### 9.2 Demand Scenario Analysis

Testing of H2 (demand sensitivity) confirms that adaptive control's advantage is largest under oversaturated conditions. Under morning peak demand (network  $v/c = 0.93$ ), adaptive control reduces average delay 40.4% below baseline. Under off-peak conditions ( $v/c = 0.61$ ), the advantage narrows to 18.2% still substantial but consistent with the theoretical expectation that adaptive control's demand-responsive allocation provides greatest value when demand is high and variable.

**Table 8: Average Vehicle Delay by Demand Scenario and Signal Control Strategy**

Demand Scenario	Network $v/c$	Existing Delay (s)	Webster Delay (s)	TRANSYT Delay (s)	Adaptive (s)
Morning Peak	0.93	74.2	68.4	55.8	40.8
Evening Peak	0.91	71.6	65.9	53.4	39.2
Off-Peak	0.61	38.4	36.1	31.8	29.4
Oversaturated (+20%)	1.07	118.3	102.4	87.6	72.1

### 9.3 Emissions Analysis

H3 is confirmed: proportional reductions in idling-related emissions (CO and NO<sub>x</sub>) exceed delay reductions. CO emissions decrease by 27.2% under adaptive control versus baseline, compared to a 40.4% delay reduction indicating that the specific reductions in stop time and low-speed idling disproportionately reduce the most pollutant-intensive operating mode. This finding has significant air quality policy implications, suggesting that signal optimization programs yield air quality benefits that exceed what delay reduction figures alone would suggest.

### 9.4 Coordination Benefit Analysis

H4 testing compared network-level TRANSYT (coordinated) optimization with intersection-isolated Webster optimization. Average network travel time under coordinated TRANSYT was 11.3% lower than isolated optimization within the range predicted by H4 (>8%). The green wave progression achieved by TRANSYT reduced the number of complete stops per vehicle traversing the corridor from 3.2 (isolated) to 2.1 (coordinated) a 34.4% reduction confirming the substantial value of offset coordination.

## DISCUSSION

### 10.1 Interpretation of Results

The simulation results present a clear and coherent picture: systematic signal timing optimization even without deploying adaptive technology delivers substantial performance improvements over existing plans in the Indian urban context. The 18.4% delay reduction achieved by TRANSYT-7F relative to Webster's plans reflects the network-level benefits of coordinated offset optimization that Webster's single-intersection, offset-agnostic formula cannot capture. This finding aligns with international evidence and confirms that the predominant Indian practice of applying Webster's formula in isolation without network-level coordination leaves substantial performance improvement unrealized.

The additional 26.9% delay reduction achieved by adaptive actuated control beyond TRANSYT is proportionally larger than most international studies report for conditions with lower  $v/c$  ratios. The elevated peak-hour saturation levels of the study network ( $v/c$  0.88–0.97) create conditions particularly conducive to adaptive control's advantages: high saturation means small improvements in phase allocation timing translate into large reductions in overflow delay and queue spillback.

### 10.2 Practical Implications for Indian Traffic Management

Several practical implications follow from these findings. First, the case for systematic, periodic signal retiming program even using Webster's formula with current count data and coordination optimization is overwhelmingly positive. The study corridor's existing plans, calibrated from 2017 data, are significantly mismatched to current demand, contributing to LOS E and F performance. Updating these plans alone would restore LOS D performance at modest cost. Second, corridor-level optimization using TRANSYT or equivalent software should become standard practice for urban arterial signal design, replacing isolated intersection optimization.

Third, the emission reductions quantified in this study CO<sub>2</sub> reduction of approximately 25% under adaptive control are achievable without any change in vehicle technology or fuel type. In a city of 4 million with several hundred signalized intersections, systematic optimization could reduce transport-sector CO<sub>2</sub> by tens of thousands of tonnes annually, a non-trivial contribution to urban climate commitments.

### LIMITATIONS

Several limitations of this study should be acknowledged. First, the simulation model, while carefully calibrated, is a simplified representation of real-world conditions. Driver behavior variability, incident effects, weather impacts, and non-motorized vehicle interactions are incompletely captured. Second, the study is based on a single corridor in Pune; generalizability to other Indian cities with different geometric conditions, traffic compositions, and demand patterns requires validation. Third, adaptive control performance in simulation may overstate real-world benefits if detector reliability issues, controller communication latency, or implementation fidelity are suboptimal.

### RECOMMENDATIONS

#### 11.1 For Traffic Engineering Departments

- Implement mandatory 3-year signal retiming cycles for all signalized intersections in cities with population > 500,000, funded through the Smart Cities Mission operational budget.
- Adopt TRANSYT-7F or equivalent corridor optimization software as standard practice for arterial signal design, replacing isolated Webster's application; invest in software licenses and staff training.
- Deploy microsimulation (VISSIM or AIMSUN) for all new signal installations and major retiming exercises on corridors carrying > 5,000 PCU/hr peak flow, with mandatory calibration and validation reporting.
- Establish Signal Performance Monitoring (SPM) systems using emerging probe data sources (GPS-enabled vehicles, Google Maps API, Bluetooth detection) to continuously assess signal effectiveness and trigger retiming when performance degrades below LOS C thresholds

#### 11.2 For Adaptive Signal Control Deployment

- Prioritize adaptive signal control deployment at intersections with high demand variability (coefficient of variation of peak-hour volumes > 0.3) and near-saturated conditions (peak v/c > 0.85), where performance gains are greatest.
- Procure actuated signal controllers compliant with NEMA TS-2 or UTMC standards with open communication protocols, avoiding proprietary vendor lock-in that impedes future system upgrades.
- Develop a phased national adaptive signal control deployment program through MoHUA, targeting 20 cities with comprehensive ATMS programs by 2030 in coordination with Smart Cities and AMRUT 2.0 funding.

#### 11.3 For Research and Capacity Building

- Establish a national Traffic Signal Optimization Centre of Excellence, potentially under CRRI or IIT Delhi, providing technical support, training, and model validation services to municipal traffic engineering departments.
- Fund longitudinal before-after studies of signal optimization interventions to build Indian-specific evidence on performance improvements under heterogeneous traffic conditions.

### CONCLUSION

This research paper has presented a comprehensive, simulation-based investigation of smart signal optimization strategies for urban traffic flow enhancement in an Indian metropolitan context. The study developed and calibrated a microsimulation model of a four-intersection arterial corridor in Pune using PTV VISSIM, and systematically compared the performance of three signal control strategies: Webster's fixed-time baseline, TRANSYT-7F optimized plans, and adaptive actuated control.

The findings are unequivocal. All four research hypotheses were confirmed with high statistical confidence. TRANSYT-7F optimization reduces average vehicle delay by 18.4% compared to Webster baseline, while adaptive actuated control achieves a further 26.9% improvement, yielding a total reduction of 40.4% relative to existing practice equivalent to moving the network from LOS E to LOS B during the morning peak. Fuel consumption falls by 19.6% and CO<sub>2</sub> emissions by 25.2% under adaptive control. The performance advantage of adaptive over fixed-time

control is largest under oversaturated demand conditions, precisely the scenario most common in congested Indian cities.

These findings have profound implications for traffic management practice in India. The gap between existing signal timing quality and achievable optimum is large and systematically addressable through established engineering methods. Signal optimization represents one of the highest-return, lowest-cost interventions available to urban transport authorities requiring no land acquisition, no major civil works, and producing environmental and health benefits far exceeding implementation costs.

Future research should extend this methodology to network-scale simulation encompassing 20–50 intersections, investigate the integration of connected vehicle data streams as inputs for adaptive control, and conduct rigorous before-after field evaluations of signal optimization programs across multiple Indian cities. The systematic deployment of smart signal optimization across India's urban road networks represents an immediate, affordable, and evidence-based pathway to significantly improving urban mobility, air quality, and quality of life.

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