International Journal of Engineering Research Excellence and Applied Science (IJEREAS)

Volume-IV (Issue 2) – April- June 2026 ISSN: 3048-5355

A SYSTEMATIC REVIEW OF TRAFFIC SIGNAL DESIGN METHODOLOGIES AT URBAN INTERSECTIONS UNDER HETEROGENEOUS TRAFFIC CONDITIONS

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Abstract— Urban intersections in developing nations face unprecedented challenges due to rapid vehicle ownership growth and highly heterogeneous (mixed) traffic conditions. This paper presents a systematic review of contemporary research focusing on traffic signal design at urban intersections, primarily evaluating the integration of Indian Roads Congress (IRC:93) guidelines, Webster's optimization method, and micro-simulation techniques. By synthesizing recent field studies across diverse Indian cities, this review maps key operational parameters including Passenger Car Unit (PCU) factors, local saturation flow variations, and geometric constraints. The analysis reveals critical limitations in relying solely on static theoretical values from design manuals under highly mixed traffic streams. Finally, this paper outlines key research gaps, emphasizing the transition toward adaptive, real-time control systems and inclusive multi-modal pedestrian planning.

Keywords— Traffic signal design, Mixed traffic, Webster's method, IRC guidelines, Passenger Car Unit, Saturation flow.

I. INTRODUCTION

Road intersections serve as the primary operational bottlenecks within urban transit networks, exhibiting significantly lower capacity than mid-block sections. With rapid global urbanization and rising vehicle ownership rates, these conflict points experience severe traffic congestion, prolonged vehicular delays, and heightened accident frequencies. In developing countries like India, managing intersections is uniquely challenging due to the heterogeneous nature of traffic streams, where vehicles of vastly different static and dynamic characteristics (e.g., two-wheelers, cars, auto-rickshaws, buses, and heavy commercial trucks) share the same right-of-way without lane discipline.

Historically, traffic signals featuring three-color indications (red, yellow, green) have served as the benchmark mechanism to regulate conflicting movements safely and efficiently. Optimizing signal phases and cycle lengths is critical; poorly timed phases aggravate queue lengths and emissions, whereas mathematically optimized intervals minimize total intersection delay and reduce conflict-induced collision risks.

While traditional frameworks depend heavily on static calculations—such as those popularized by F.V. Webster and regional design standards like the Indian Roads Congress (IRC)—modern urban densities require a critical re-evaluation of these methods. This review paper aims to comprehensively synthesize recent empirical literature surrounding intersection signal design in mixed traffic environments, evaluate the efficacy of current methodologies, and establish a clear roadmap for deploying next-generation adaptive traffic controls.

II. METHODOLOGY

To ensure a rigorous, reproducible synthesis of literature, a systematic search strategy was deployed across primary academic databases, including Scopus, Google Scholar, and the Indian Citation Index. The search was bounded by a publication window of 2017 to 2026 to capture contemporary advancements in urban intersection management.

Papers were selected based on following criteria:

Inclusion: Peer-reviewed empirical case studies evaluating signal design, studies focusing on mixed traffic flows, and papers applying standard analytical or simulation framework.

Exclusion: Non-English publications, studies exclusively evaluating pure homogeneous lane-disciplined highway traffic, and general textbooks. A total of eight core empirical studies reflecting distinct regional urban intersections in India were selected for comparative synthesis.

III. HEMATIC SYNTHESIS OF LITERATURE

Current literature can be systematically classified into three dominant themes: empirical manual design, geometric/safety re-engineering, and computer-aided micro-simulation models.

A. Empirical Manual Design and Webster's Application

A significant portion of the literature focuses on adjusting fixed-time signal settings using peak-hour manual traffic counts. Researchers like Chiranjeevi et al. (2022) at Gandhi Circle in Davanagere, and Pal and Tripathi (2019) in Lucknow, utilized manual data logged over pre-defined time intervals to compute optimum cycle lengths. Similarly, Parmar and Lalit (2018) captured morning and evening peak volumes in Rajkot city to evaluate traffic performance indicators. These studies universally demonstrate that applying Webster's standard cycle length formula:

$$C_0 = \frac{1.5L + 5}{1 - Y}$$

Where L is total lost time per cycle and Y is the sum of critical flow ratios can significantly lower immediate congestion levels compared to un-signalized or poorly timed baseline settings. However, these approaches are uniformly constrained by their reliance on static, historic data that fails to adjust for hourly dynamic traffic fluctuations.

B. Heterogeneous Traffic and Saturation Flow Dynamics

A critical sub-theme in Indian traffic engineering is the conversion of diverse vehicle types into a uniform metric using Passenger Car Units (PCU) . Kumar and Nitin Kumar (2018) conducted detailed traffic surveys in Yamunanagar City to establish that accurate, local estimation of PCU values is mandatory for capacity analysis under mixed traffic conditions. The friction between theoretical guidelines and real-world conditions is highlighted by Marfani et al. (2020) in Surat. Their research compared field data directly with standard models prescribed by the Indian Roads Congress (IRC) and the Highway Capacity Manual (HCM). They proved that actual saturation flow in highly congested urban environments diverges drastically from static theoretical assumptions due to variations in lane width, vehicle distribution, and erratic driving behavior. Consequently, relying blindly on generic design manuals without adjusting for local saturation coefficients results in compromised signal efficiency.

C. Geometric Interventions and Safety Metrics

Signal optimization cannot be separated from the physical geometry of the junction. Rambabu et al. (2017) demonstrated in Jodhpur that combining standard IRC signal phase adjustments with proper junction layout modifications reduces structural bottlenecks. Achu et al. (2019) extended this in Kottayam by conducting collision and conflict analysis, concluding that improper geometric layouts are a root cause of intersection accidents. They recommended physical channelization, dedicated pedestrian crossings, and turning lanes to work in tandem with signal phases to decrease collision metrics.

D. Micro-Simulation Advancements

To bridge the gap between static calculations and dynamic field conditions, recent work has integrated computational simulation models. Abbas Ali and Tahseen Sultana (2022) studied unsignalized junctions in Mahabubnagar by pairing traditional Webster formulations with micro-simulation software. Their findings proved that verifying mathematical models through micro-simulation yields highly realistic delay profiles, allowing engineers to test signal phase efficiency virtually before field deployment, reducing unexpected traffic conflicts..

E. Comparative Synthesis Matrix

To present a concise assessment of the current state of research, the following matrix compiles, contrasts, and evaluates the primary empirical literature reviewed.

Author(s) & Year	Study Location	Core Methodology	Key Parameters Investigated	Major Finding / Contribution	Documented Limitation
Rambabu et al. (2017)	Jodhpur	Manual Volume Count + IRC Phase Design	Traffic Volume, Signal Phases	Phase optimization significantly mitigates urban bottleneck delays.	Lacks micro-simulation validation or dynamic variance checks.
Parmar & Lalit (2018)	Rajkot	Peak-Hour Survey + Webster's Method	Vehicle Mix, PCU, Cycle Length	Auxiliary lanes paired with Webster timing drastically clear queues.	Pedestrian movement cycles were completely omitted.
Kumar & Kumar (2018)	Yamunanagar	Traffic Classification + Capacity Analysis	PCU Factors, Effective Green Time	Proved accurate PCU calculation is vital for mixed traffic transit.	Data collected over limited seasonal intervals.
Pal & Tripathi (2019)	Lucknow	Unsignalized Junction Movement Analysis	Approach Patterns, Target Cycle Length	Transitioning unsignalized areas to fixed signals enhances safety.	Relies entirely on static data without real-time adjustments.
Achu et al. (2019)	Kottayam	Conflict Observation + Geometric Mapping	Accident Records, Conflict Points	Outlined geometric flaws as principal triggers for urban collisions.	Did not integrate automated digital conflict-tracking tools.
Marfani et al. (2020)	Surat	Empirical Field Validation vs. IRC/HCM	Saturation Flow, Vehicle Fractions, Width	Confirmed field saturation flows deviate heavily from manual limits.	Did not provide an optimized mathematical model to replace guidelines.
Chiranjeevi et al. (2022)	Davanagere	Manual Tallying + Multi-Approach Timing	Approach Volume, Cycle Optimization	Tailored phase intervals lower peak hours congestion arrays.	Heavily dependent on manual human data collection protocols.
Ali & Sultana (2022)	Mahabubnagar	Webster Framework + Micro-Simulation	Queue Delays, Network Performance	Simulation techniques offer realistic delay cuts pre-implementation.	High computational overhead; lacks real-time sensor loops.

IV. *IDENTIFIED RESEARCH GAPS*

By conducting an exhaustive analysis of the literature matrix, three distinct gaps have been identified in contemporary traffic signal research within the regional context:

Absence of Real-Time Adaptive Control Systems: The vast majority of standard research continues to rely on historical, manual counts to establish rigid, fixed-time cycles. These plans fail during irregular incidents, inclement weather, or erratic spikes in volume. There is a profound deficit in research exploring the integration of adaptive control architectures (e.g., computer-vision vehicle tracking or inductive loop sensors) optimized for the erratic lane-less behavior of heterogeneous streams.

Disregard for Multi-Modal and Pedestrian Safety: The standard application of IRC and Webster's methods focused heavily on maximizing motor vehicle throughput and minimizing automobile delays. Pedestrian clearance intervals, sidewalk integration, and micro-mobility paths are frequently excluded from calculations, leading to intersections that are inherently dangerous for vulnerable road users.

Mismatched Theoretical Baseline Parameters: As confirmed by saturation studies, the baseline coefficients provided in national standard manuals often fail to mirror the chaotic operational dynamics of modern saturated cities. Research has yet to provide an updated mathematical model that factors in vehicle-type interaction penalties within a shared lane space.

V. CONCLUSION AND FUTURE DIRECTIONS

This review underscores that while standard methodologies like Webster's optimization and IRC guidelines provide a foundational baseline for traffic signal design, their implementation in highly mixed traffic conditions requires localized calibrations. Passive, fixed-time models are insufficient for modern urban intersections. Geometric enhancements, such as channelization and auxiliary turning lanes, must be structurally integrated with signal phase planning to yield sustainable safety outcomes.

Future research paths must pivot toward:

- Constructing robust mathematical variations of Webster's equation that dynamically recalculate PCU values in real-time.
- Utilizing automated machine-learning vision algorithms to capture actual saturation indices.
- Mandating multi-modal phase configurations that balance vehicular delays with pedestrian safety criteria to build resilient, sustainable urban infrastructure.

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