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Why Traffic Signals Fail in Sri Lanka: Reviewing the Realities of Heterogeneous Traffic Dynamics

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Abstract: Traffic signal design in developing countries frequently underperforms due to the direct application of classical models—Webster's delay formula, HCM, ARR123, and ORN13—developed for homogeneous, lane-disciplined traffic conditions. Sri Lankan intersections exhibit fundamentally different characteristics: heterogeneous vehicle streams comprising motorcycles, three-wheelers, non-motorized vehicles, and pedestrians operating without strict lane discipline under geometric constraints. This systematic review synthesizes empirical evidence explaining why conventional signal design methods fail in such contexts. Following PRISMA principles, 138 records were screened, yielding 41 high-quality references spanning foundational theory, classical assumptions, regional adaptations, and Sri Lankan empirical data. The review demonstrates that local intersections systematically violate foundational assumptions regarding lane usage, headway uniformity, start-up behavior, and pedestrian compliance. Observed saturation flows reach 2574 pcu/h/lane—substantially exceeding HCM benchmarks—while behaviors such as motorcycle seepage, lateral filtering, initial surge, and dynamic clustering create discharge patterns that static PCU values cannot capture. A mathematical framework is presented mapping these deviations to quantifiable variables: lateral efficiency, surge discharge dynamics, dynamic vehicle equivalence, headway expansion, and geometric constraints affecting intersection capacity. The paper concludes by proposing context-sensitive design pathways incorporating dynamic PCU factors, behavioral modeling, and simulation-based calibration using SIDRA and SUMO to support locally relevant signal control methodologies.

Keywords: Heterogeneous Traffic, Mathematical Framework, Signal Optimization, Traffic Signals

1. Introduction

Traffic signal design plays a central role in ensuring operational efficiency and safety at urban intersections. Optimal signal timing minimizes delay, reduces queue spillback, improves fuel efficiency, and enhances the overall level of service. Classical signal design methods, the Highway Capacity Manual (HCM) [1], ARR123 [2], and ORN13 [3] based on Webster's delay model [4] are grounded in assumptions of homogeneous, lane-disciplined, and predominantly under-saturated traffic flow. These models were developed in environments where traffic streams are car-dominated, headways are stable, pedestrian behaviour is predictable, and lane usage is consistent.

In contrast, traffic conditions in developing countries, particularly Sri Lanka, are fundamentally different. Sri Lankan intersections carry highly heterogeneous traffic comprising motorcycles, three-wheelers, buses, heavy vehicles, non-motorized modes, and pedestrians, all interacting without strict adherence to lane discipline. Vehicle behaviour is characterised by seepage, lateral shifts, clustering at the stop line, initial surge during the start of green, variable pedestrian compliance, and localized geometric constraints. These behaviours significantly influence saturation flow, queue discharge, and signal performance, resulting in outcomes that classical methods cannot reliably predict.

The mismatch between theoretical foundations and real-world operations has led to recurrent signal failures, long queues, and persistent oversaturation at major intersections in Sri Lanka. Saturation flows observed in practice often exceed global benchmarks, revealing a clear disconnect between standardized design assumptions and the realities of mixed traffic environments.

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Despite these well-recognized discrepancies, conventional signal design principles continue to be applied without sufficient contextual calibration, resulting in suboptimal performance and widespread inefficiencies.

The existing literature addresses mixed traffic, oversaturation, lane discipline, and dynamic vehicle behaviour across multiple developing countries. However, there is still a lack of structured synthesis explaining precisely *why* classical models fail in Sri Lanka, *which assumptions break down*, and *how* those deviations affect signal timing outputs. This gap inhibits the development of a locally relevant, context-sensitive signal design framework.

Figure 1 illustrates the logical progression from traffic flow fundamentals to conventional signal timing methods, and how deviations in heterogeneous traffic environments lead to failures in intersection performance

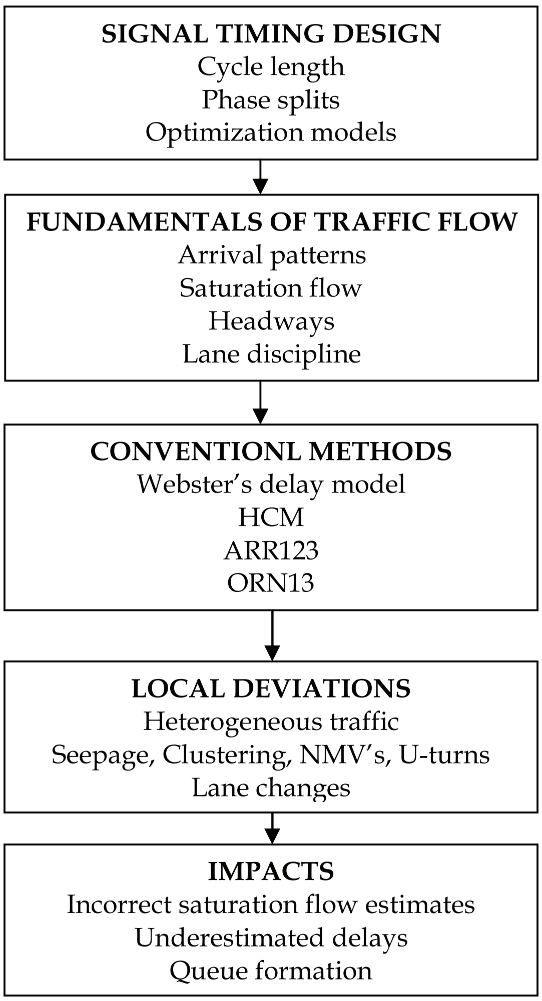

Figure 1 – Flow Chart of Sri Lankan Traffic Signal Design

Accordingly, this paper presents a systematic review focused specifically on Sri Lanka. It examines global theoretical foundations, evaluates their assumptions, and links them to behavioural and operational deviations observed in Sri Lankan traffic. A conceptual flow is developed connecting (i) Traffic flow fundamentals, (ii) Classical model assumptions, (iii) Local behavioural deviations, and (iv) Impacts on signal timing and performance. The aim is to provide a structured, evidence-based explanation of why conventional tools fail and to guide future development of Sri Lanka–specific signal control methodologies.

2. Review Methodology

This paper adopts a systematic review methodology to examine the applicability and limitations of classical traffic signal design methods under Sri Lankan heterogeneous traffic conditions. The approach follows the principles of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis), adapted for transport engineering research, ensuring transparency and reproducibility in the identification, screening, and synthesis of relevant studies.

2.1 Scope of the Review

The review focuses on literature across several thematic areas: foundational traffic flow theory relevant to signalized intersections; classical signal design approaches and their underlying assumptions, including Webster, HCM, ARR123, and ORN13; mixed-traffic behaviour and deviations from idealized flow such as motorcycle clustering, seepage, lateral movement, non-motorized vehicles, heavy vehicles, pedestrian behaviour, and U-turn effects; Sri Lankan and regional empirical evidence including saturation flow measurements and pedestrian compliance; and regional methodologies such as the Indo-HCM and Malaysian HCM.

The goal is to link theoretical foundations to model assumptions and observes how Sri Lankan traffic deviations result in consequences on signal design performance.

2.2 Search Strategy

A structured search was conducted across major academic databases and institutional repositories:

- Scopus
- Web of Science
- IEEE Xplore

- ScienceDirect
- TRB Publications
- SpringerLink
- Taylor and Francis Online
- IESL Transactions Archive
- University of Moratuwa archives

Grey literature sources were also included, namely: HCM, ARR123, ORN13, Indo-HCM, and M-HCM.

2.3 Search Terms

Search terms combined keywords from three domains:

Classical Signal Design Models

- "Webster's delay model"
- "signalized intersection capacity"
- "saturation flow model"
- "HCM signalized intersections"
- "ARR123 signal timing"
- "ORN13 developing countries"

Heterogeneous / Non-Lane-Disciplined Traffic

- "heterogeneous traffic flow"
- "motorcycle-dominated intersections"
- "traffic seepage behaviour"
- "initial surge behaviour"
- "dynamic PCU"
- "lateral movement motorcycles"
- "non-motorized vehicle interaction"

Sri Lanka–Specific Queries

- "saturation flow Sri Lanka"
- "pedestrian compliance Sri Lanka"
- "mixed traffic Sri Lanka"
- "signal design Sri Lanka"

Boolean operators ("AND", "OR") were used to refine the search and ensure relevance to developing-country mixed traffic.

2.4 Inclusion and Exclusion Criteria

2.4.1 Inclusion criteria

Studies were included if they addressed signal design, saturation flow, intersection performance, or traffic behaviour; examined mixed, heterogeneous, or non-lane-disciplined traffic conditions; incorporated empirical measurements, behavioural analysis, simulation, or methodological models; focused on developing countries, particularly Sri Lanka and South/Southeast Asia; were published between 1957 and 2024; and belonged to peer-reviewed journals, conference papers, manuals, dissertations, or authoritative research reports.

2.4.2 Exclusion criteria

Studies were excluded if they focused on uninterrupted-flow facilities such as freeways or expressways, addressed only homogeneous traffic environments typical of North America or Europe with no relevance to heterogeneity, lacked methodological or empirical detail, examined non-road modes such as rail, maritime, or aviation, or presented purely theoretical frameworks without applicability to heterogeneous traffic conditions.

2.5 Study Selection Process

The systematic search produced 138 records across databases and grey literature, with 112 unique studies retained after duplicate removal. Title and abstract screening excluded 53 unrelated to signalized intersections, heterogeneous traffic, or developing-country contexts, leaving 59 for full-text review. Of these, 9 were excluded for weak methodology, 5 for lacking relevance to signal timing, and 4 for being purely theoretical. The final synthesis comprised 31 peer-reviewed studies and 10 manuals or technical reports, including HCM, ARR123, ORN13, Webster, Indo-HCM, M-HCM, and foundational works on oversaturation and simulation. In total, 41 high-quality references formed the core dataset, consistent with PRISMA stages of identification, screening, eligibility, and inclusion as shown in Figure 2.

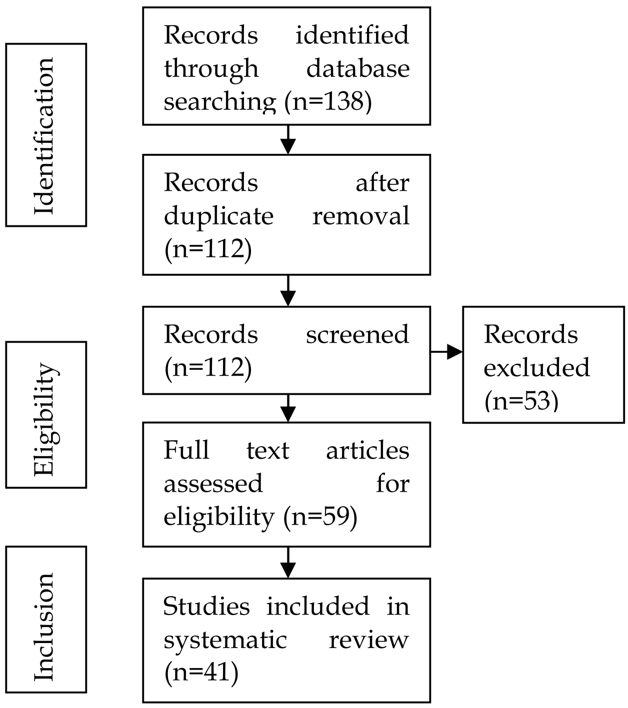

Figure 2 – Flow Chart of Study Selection Process

2.6 Synthesis and Analytical Frameworks

A thematic synthesis approach was used to organise and interpret the included studies. The analysis was structured into four interrelated dimensions:

Traffic Flow Fundamentals

Foundational theories on volume, speed, density, saturation flow, headways, and lane discipline

Classical Signal Design Assumptions

Assumptions embedded in Webster, HCM, ARR123, and ORN13, including uniform headways, fixed PCU values, lane-based discharge, and stable flow.

Sri Lankan Traffic Deviations

Empirically observed behaviours such as seepage, motorcycle clustering, dynamic lateral movement, heavy vehicle impacts, NMV interactions, pedestrian non-compliance, and U-turn effects

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Consequences on Signal Design Performance

Impact on saturation flow estimation, cycle length determination, lost time, queue discharge, residual queues, oversaturation, and signal failure.

3. Classical Theories and Global Practices

The evolution of traffic signal design was driven by classical studies focused on optimizing fixed-time operations under homogeneous, lane-disciplined traffic typical of developed countries. Foundational contributions by Webster [4], Gazis and Potts [5], Gazis [6], Gartner, Little and Gabbay [7], and Michalopoulos and Stephanopoulos [8] established the theoretical basis for delay estimation, cycle length optimization, and efficiency balancing across phases, subsequently shaping international design manuals and widely used software tools.

3.1 Webster's Delay Model and Foundational Theory

Webster's [4] model provides the seminal basis for estimating optimum cycle length to minimize delay at isolated intersections, using parameters such as green time, cycle length, saturation flow, and lost time under assumptions of uniform discharge and under-saturated flow. While widely applied, its reliance on constant saturation flow, ideal lane discipline, and minimal interactions limits applicability in heterogeneous or oversaturated context. Refinements by Cheng et al [9] and Akçelik [10] introduced shared lanes, turning movements, and stop penalties, but retained Webster's core theoretical framework.

3.2 Highway Capacity Manual Method

The Highway Capacity Manual [1] extends Webster's [4] theory to evaluate delay, capacity, and level of service using a base saturation flow of 1900 pcu/h/ln, adjusted for geometric and operational factors. Although analytically robust, its delay-oriented framework assumes homogeneous, lane-disciplined traffic, which results in underestimated saturation flow and overestimated delay under the mixed, non-lane-based conditions common in developing countries, thereby restricting its applicability.

3.3 Australian ARR123 Method

The Australian Road Research Report 123 [2] refines Webster's delay model by using Through Car Equivalents (TCU) rather than PCU to better represent diverse vehicles and turning movements, and highlights coordination through signal offsets—a foundation for systems like SCATS—to reduce stops and delay. It also supports flexible optimisation for objectives such as minimizing delay or fuel use. However, ARR 123 [2] still assumes lane discipline and stable flows, limiting its direct applicability in mixed traffic with lateral movements and irregular vehicle behaviour.

3.4 Overseas Road Note (ORN13) Method

The UK's Overseas Road Note 13 [3] adapts Webster's [4] delay-based approach for low- and middle-income contexts by offering simplified formulas for minimum and practical cycle times, recommending operation at up to 90% capacity, and limiting cycles to 90–120 s to control queues. It accounts for heterogeneous traffic through PCU conversions derived from empirical studies in India, Indonesia, and Egypt. However, ORN 13 [3] still relies on lane-based flow and fixed PCU values, reducing accuracy in non-lane-disciplined or oversaturated conditions common in South and Southeast Asia.

3.5 Summary of Classical Approaches

Collectively, these classical theories and manuals provide the core analytical foundation for modern signal design, offering clarity and structured methodologies for planning and evaluation. Yet their reliance on assumptions of homogeneous, lane-disciplined, equilibrium flow limits their usefulness in developing countries. With South Asian intersections increasingly characterized by mixed traffic and near-saturated conditions, these limitations highlight the need for updated methods that better capture the dynamics of heterogeneous traffic environments.

4. Deviations from Classical Conditions

Idealized conditions rarely occur even in homogeneous traffic, and deviations from classical assumptions become far more pronounced in heterogeneous settings. Mixed, non-lane-disciplined streams like cars, motorcycles, buses, bicycles, and auto-rickshaws create complex interactions that classical models such as Webster [4], HCM [1], ARR 123 [2], and ORN 13 [3] cannot adequately represent, as they rely on fixed or geometry-based saturation flow values. Empirical evidence shows this gap: Mondal and Gupta [11] introduced dynamic PCU factors responsive to vehicle mix and geometry, while Perera and Bandara [12] observed Sri Lankan saturation flows reaching 2574 pcu/h/lane, far above HCM estimates. These results highlight the need for recalibrated models that reflect heterogeneous, non-lane-based traffic behaviour.

4.1 Heavy Presence of Motorcycles

Motorcycles dominate traffic in many developing countries, forming clusters that challenge the uniform, lane-based assumptions of classical manuals. To capture their influence, Nguyen [13] introduced the Motorcycle Unit (MCU), reporting flows as high as 11,300 MCU/h—about 5.8 times the HCM's 1900 PCU/h benchmark. Applying these values to Sri Lanka requires caution given differences in vehicle composition and rider behaviour. Local observations by Wimalasiri et al. [14] show motorcycles (≈30%) surging to the queue front, increasing start-up delay and disturbing saturation headways. These findings reinforce the need for motorcycle-specific measures such as MCU in delay, capacity, and LOS estimation.

4.2 "Seepage" of Smaller Vehicles

Seepage refers to how small vehicles, particularly motorcycles,filter or split lanes to move through gaps between larger vehicles at intersections. Though these manoeuvres raise effective capacity, classical manuals ignore them by assuming lane-bound, uniform flow. Singh and Rao's [15] Seepage Behavior Model (Figure 3) illustrates motorcycles advancing through gaps to the stop line, increasing discharge rates. Sri Lankan findings by Wimalasiri et al. [14] similarly show motorcycles zigzagging and surging forward, cutting start-up delay and disrupting saturation headways. Recognising seepage is therefore essential for more accurate signal timing, capacity estimates, and safety analysis in heterogeneous South Asian traffic.

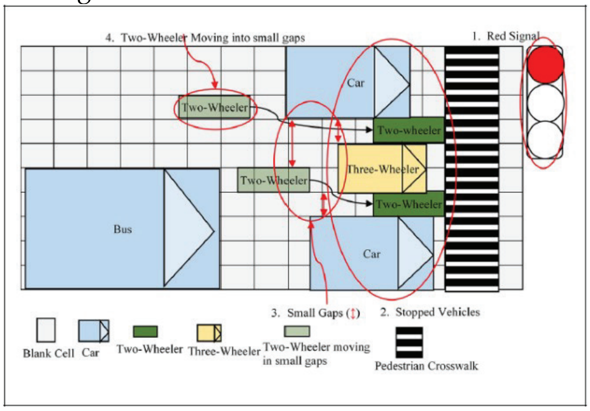

Figure 3 – Seepage Behaviour Model (Singh and Rao [15])

4.3 Non Lane based Movement of Motorcycles

Motorcycles differ from cars by using lateral space flexibly, frequently shifting sideways, overtaking, filtering, and forming dynamic lanes, which affects traffic performance, lane utilization, and intersection capacity [16,17]. Figure 4 [16] illustrates the concept of safety space, showing how riders adjust speed when encroachment occurs to maintain a personal buffer.

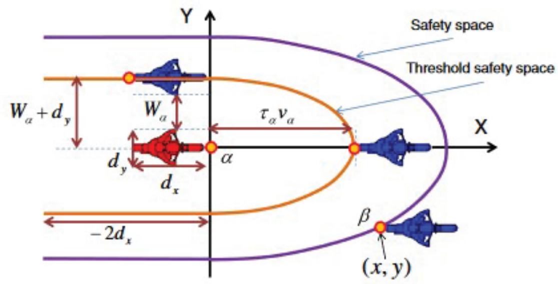

Figure 4 – Safety Space and Threshold Safety Space

Classical manuals and models like Webster [4] assume lane-based, car-dominated flow with uniform saturation and fixed trajectories, overlooking motorcycles' start surges, lateral movement, and side-by-side travel. Although the Malaysian [18] and Indian [19] HCMs introduce adjustment factors for surge effects, they still miss the full impact of non-lane-based dynamics. Integrating motorcycle-specific behaviours, particularly safety space and lateral movement patterns (Figure 4), is crucial for realistic signal timing, capacity estimation, and intersection analysis in motorcycle-rich environments [12, 20].

4.4 Initial Surge and Clustering Behaviour of Vehicles

The initial surge at signalized intersections in developing countries occurs when motorcycles and auto-rickshaws cluster at the stop line during the red phase and discharge rapidly at green. Vien, Ibrahim, and Mohd [21] show that motorcyclists weave forward during red, forming dense groups that generate high initial discharge rates through lateral movement and lane sharing. Classical lane-based models assume car-dominated traffic and uniform headways with start loss, and therefore fail to capture this short-term "start gain." Although the Malaysian [18] and Indian [19] HCMs introduce surge or adjustment factors, they do not fully represent clustering, weaving, and non-lane-based behaviour in heterogeneous traffic. Proper representation of these effects is essential for realistic capacity and delay estimation. Figure 5 illustrates this phenomenon.

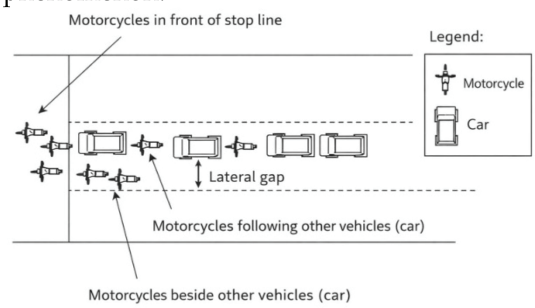

Figure 5 – Phenomenon of Initial Surge of Motorcycles

4.5 Effect of Non-Motorised Vehicles and Auto Rickshaws (Three-Wheelers)

Non-motorized vehicles and slow-moving motorized vehicles, such as auto-rickshaws, significantly influence traffic operations in developing countries [22, 23]. Rahman, Okura, and Nakamura [22] showed that intersection discharge increases as rickshaw share rises to about 50% because of improved lane utilization, but declines at higher shares due to their lower speeds and acceleration, with PCU values increasing as their flow proportion grows (Figure 6).

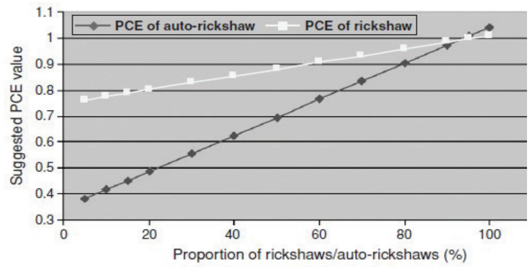

Figure 6 – Suggested PCE (PCU) Values for Rickshaws and Auto Rickshaws for Capacity Analysis

NMVs like bicycles and handcarts further introduce variable speeds and erratic lateral movements, frequently encroaching into main lanes [23]. These behaviors deviate from classical traffic models that rely on fixed PCU values, underscoring the importance of explicitly accounting for NMVs and slow three-wheelers in capacity, signal timing, and performance analysis for heterogeneous traffic (Figure 6 [22])

4.6 Effect of Frequent Lane Changes

Frequent lane changes in mixed traffic are classified as Mandatory (MLC) and Discretionary (DLC), arising from obstacles or travel-time optimisation [24, 25]. These movements disrupt flow, increase lateral interactions, and may reduce discharge rates under congestion, though temporary gains can occur [26, 27]. Classical models assume strict lane discipline and do not capture motorcycle and auto-rickshaw micro-manoeuvres [13, 15]. Sri Lankan studies confirm frequent MLC and DLC behaviour at Colombo intersections, significantly affecting discharge and performance [27]. Accurate representation of lane changes is therefore essential for realistic signal timing and capacity estimation, with dynamic lane and safety-space models offering effective tools [17, 28].

4.7 Effect of Heavy Vehicles

Heavy vehicles differ from passenger cars in size, mass, and performance, leading to longer clearance times, slower acceleration, and reduced deceleration, which lower intersection capacity and increase delays [29]. Classical manuals like ARR 123 [2] classify vehicles simply as Light or Heavy, neglecting variations among smaller commercial vehicles, modern HGVs, and mixed-lane interactions in developing countries with motorcycles, auto-rickshaws, and NMVs [29, 30]. Fixed PCU values used in traditional models cannot capture dynamic interactions, behavioural differences, or heavy-vehicle effects on traffic stability, shockwaves, and congestion. Context-sensitive modelling that includes heavy-vehicle dynamics is thus essential for realistic signal timing and intersection performance.

4.8 Effect of Bicyclists Sharing Road Space with Motorised Traffic

Conventional manuals often ignore bicycles, assuming segregated operation and assigning zero PCU. In developing countries, bicycles share lanes with motorized vehicles, affecting intersection performance. Chen, Shao and Yue, (2007) [31] noted conflicts during amber phases, hesitation, and incomplete intersection clearance, while Huang and Wu [32] observed group travel with variable speeds and gap acceptance, increasing heterogeneity. These behaviours violate lane-disciplined assumptions, emphasizing the need for signal design methods that explicitly account for bicyclist dynamics to improve capacity, delay, and safety predictions.

4.9 Effect of Pedestrians

Pedestrians significantly affect safety and efficiency at signalized intersections. While high compliance improves flow, non-compliance raises conflicts and delays. In developing countries, pedestrian modelling is limited by enforcement and infrastructure. Studies show variability: in Sri Lanka, average walking speeds are often below 1.5 m/s with 61.17% signal compliance [33], compared to 44% in India and 68–79.7% internationally; Marisamynathan and Perumal [34] observed 1.2–1.4 m/s, differing from standard assumptions. Classical manuals assume uniform speeds and full compliance, potentially underestimating clearance times and overestimating intersection performance. Accurate signal design requires region-specific pedestrian data reflecting actual speeds, compliance, and vehicle interactions [33, 34].

4.10 Effect of U-Turns

U-turning vehicles typically operate at lower speeds than right-turning vehicles, increasing headways and reducing saturation flow, particularly in shared turning lanes. Classical manuals assume uniform turning behaviour and fixed lane usage, limiting applicability in heterogeneous traffic with frequent U-turns. Empirical studies report that U-turns increase headways by about 27% [35] and significantly reduce capacity when exceeding 40% of shared turning movements [36]. Sri Lankan studies by Abeygunawardana and Wickramasinghe [37] also show that U-turns at median openings increase follower delays and reduce effective intersection capacity. These findings highlight the need for context-specific signal design that explicitly accounts for U-turn effects to avoid underestimation of delay and oversaturation.

4.11 Effect of Upstream Short Lanes

Short turning lanes improve efficiency by separating turning traffic but often act as auxiliary lanes with limited storage, causing queue spillbacks under high volumes or heterogeneous traffic [38, 39]. Classical manuals like HCM [1] provide storage guidelines but inadequately address overflow, especially as motorcycles, auto-rickshaws, and bicycles exploit lateral gaps, reducing lane discipline. Probabilistic models show that lane length, green time, and phase sequencing strongly affect effective capacity, with at least 100 m recommended for optimal operation. Considering short-lane use, spillback, and signal interactions is essential for realistic timing and capacity estimation in mixed traffic.

4.12 Effect of Downstream Lane Drops

Downstream auxiliary lanes aim to improve intersection performance by promoting full lane use, but in heterogeneous, non-lane-based traffic they are often underutilized, reducing effective capacity and increasing delays [40]. Classical manuals like HCM [1] and ARR 123 [2] provide only qualitative guidance, whereas models such as SIDRA use lane-specific lengths and widths to better estimate capacity effects. Accounting for downstream geometry, lane-drop types, and heterogeneous traffic behaviour is essential for realistic signal timing and capacity estimation [1, 41].

4.13 Effect of Shared Right Turns

Shared right-turn lanes, common in space-constrained intersections in developing countries, combine right-turning and through traffic, creating conflicts that reduce efficiency. Right-turning vehicles are slower and further delayed by pedestrians and bicycles. Saturation flow rates decline as right-turning proportions increase, affected by lane number, turning radius, and NMV volumes [41]. Classical manuals use generalized adjustment factors assuming ideal lane discipline, overlooking heterogeneous interactions, which can overestimate capacity and produce suboptimal signal timings. Context-specific data are needed for accurate design in mixed-movement environments.

5. Mathematical Framework for Heterogeneous Traffic Modelling

The deviations identified in Sections 4.1 through 4.13 collectively demonstrate why classical signal design methods fail in Sri Lankan context. To transition from qualitative description to quantitative modelling, this section presents a mathematical framework that maps observed behavioural phenomena to specific variables that modify classical saturation flow estimation.

The proposed framework is conceptual and serves as an extension of classical signal capacity theory. It is intended to capture behavioural adaptations in heterogeneous traffic environments where lane discipline assumptions of HCM do not hold. The formulation is not a replacement but an augmentation, and empirical calibration is recommended for site-specific application.

5.1 Lateral Efficiency and Seepage

Classical HCM-based lane capacity models assume lane-based vehicle streams with fixed effective width. In Sri Lanka, heterogeneous traffic enables lateral seepage, where motorcycles and small vehicles form additional sub-streams within available width.

The effective lateral utilisation is expressed as:

$$N_{eff} = \frac{W_{total}}{\sum_i p_i \cdot (w_i + s_{lat,i}(v))} \quad \text{...(1)}$$

where W_{total} is total approach width (m), p_i is the proportion of vehicles class i, w_i is the physical width of vehicle class i, $s_{lat,,i}$ (v) is the dynamic safety space, shrinking as speed decreases near the stop line. This extends HCM lane-based assumptions by allowing dynamic multi-stream utilisation of road width under heterogeneous traffic conditions.

5.2 Discharge Dynamics: The Surge Function

Classical signal models assume a constant saturation flow after start-up lost time (e.g., HCM formulation). However, in Sri Lankan heterogeneous traffic, motorcycle clustering produces an initial discharge surge followed by stabilized flow.

The time-dependent discharge rate is expressed as:

$$q(t) = \begin{cases} S_{MC}, 0 \le t \le t_{surge} \\ S_{base}, \quad t > t_{surge} \end{cases} \quad \text{...(2)}$$

where S_{MC} is saturation flow of motorcycle cluster, t_{surge} is surge duration, proportional to motorcycle queue length during red and S_{base} is baseline mixed-traffic saturation flow. This formulation extends classical saturation flow theory by incorporating an initial non-linear discharge phase under heterogeneous traffic conditions.

5.3 Dynamic Vehicle Equivalence

Classical Passenger Car Unit (PCU) values assume static equivalence and do not capture speed and interaction-dependent effects in heterogeneous traffic. To address this, a dynamic area and speed-based equivalence factor is introduced:

$$\varepsilon_i = \frac{A_i + \delta_{gap}}{A_{car} + \delta_{gap}} \cdot \left(\frac{v_{car}}{v_i}\right)^{\gamma} \quad \text{...(3)}$$

where A_i is the projected area of vehicle i, δ_{gap} is the longitudinal gap requirement, v_{car}/v_i is the speed ratio and γ is the empirically calibrated friction exponent. This extends conventional PCU concepts by introducing a dynamic equivalence measure responsive to traffic composition and congestion conditions.

5.4 Flow Friction and Headway Expansion

Classical saturation flow models assume a constant mean headway (≈1.9 s). In heterogeneous traffic conditions, additional interactions such as lane changes, pedestrian crossings, non-motorized vehicles, U-turns, and turning conflicts increase effective headway.

The expanded mean headway is expressed as:

$$\bar{h} = h_{ideal} + \Delta t_{LC} + \Delta t_{ped} + \Delta t_{UT} + \Delta t_{conf} \quad \text{...(4)}$$

where; Δt_{LC} is lane change penalty, Δt_{ped} is pedestrian volume vs walking speed penalty, Δt_{UT} is empirically derived U-turn penalty and $\Delta t_{conf}$is conflict penalty from shared right turns. This extends classical headway theory by incorporating interaction-based friction effects in heterogeneous traffic streams.

5.5 Geometric Capacity Constraints

Short storage lengths and downstream bottlenecks can induce stochastic spillback even under nominally adequate capacity conditions. To represent this effect, a probability-based blockage term is introduced:

$$P_{block} = P(L_Q > L_s . \kappa) \quad \text{...(5)}$$

where; L_Q is stochastic queue length, L_S is storage length and κ is compaction factor (<1, since motorcycles fill voids). This formulation extends deterministic geometric capacity checks by introducing probabilistic spillback under heterogeneous traffic conditions.

5.6 Heterogeneous Capacity Model

Integrating these definitions yield the proposed framework;

$$C_{het} = f(N_{eff}, q(t), \varepsilon_i, \bar{h}, P_{block}) \qquad \ldots(6)$$

where intersection capacity C_{het} is expressed as a function of geometry (effective width), time (surge discharge and headway expansion), vehicle mix (dynamic equivalence), and geometry constraints (probabilistic blockage).

This formulation provides an alternative to fixed adjustment-factor approaches by explicitly linking observed heterogeneous traffic behaviour to signal performance parameters.

6. Regional and Emerging Approaches

In South and Southeast Asia, signal models are increasingly adapted to local heterogeneous traffic conditions characterized by high motorcycle and auto-rickshaw volumes, non-lane-based movements, and pedestrian interactions. The Indian HCM [19] incorporates adjustment factors for initial surge effects to reflect higher discharge rates of motorcycles and three-wheelers, while the Malaysian HCM [20] models motorcycle behaviour through patterns such as surge, oblique following, and grouping. Recent studies replace static PCUs with dynamic equivalence measures reflecting traffic composition and lane usage, with Mondal and Gupta [11] proposing dynamic PCUs and Nguyen [13] introducing Motorcycle Units (MCU) for motorcycle-dominated cities. Collectively, these context-sensitive and data-driven approaches highlight the need for adaptive signal design methods beyond classical modelling assumptions.

7. Research Gap and Future Directions

Despite decades of advancement, traffic signal methodologies remain based on assumptions of homogeneous, lane-disciplined, and under-saturated flow, conditions rarely observed in developing-country intersections. Classical models (Webster, HCM, ARR123, ORN13) fail to capture heterogeneous behaviours such as seepage, clustering, initial surge, and lateral movements, while regional adaptations (Indo-HCM, Malaysian HCM) introduce fragmented adjustment factors with limited calibration for compounded heterogeneity and oversaturation effects. The mathematical framework in Section 5 provides quantifiable variables linking these deviations to intersection capacity. Future work should focus on field validation in Sri Lanka to calibrate parameters such as saturation flow, surge ratios, and impacts of non-lane discipline, pedestrian non-compliance, U-turns, and short-lane spillbacks. Adaptive signal strategies integrating dynamic PCU/MCU models with simulation tools (SIDRA, Eclipse SUMO) are recommended. Empirically calibrated models will support realistic signal optimisation and context-sensitive design standards for heterogeneous traffic environments.

8. Conclusions

This systematic review shows that classical signal design methods (Webster, HCM, ARR123, ORN13) are not suited to Sri Lankan heterogeneous traffic due to assumptions of lane discipline and stable, uniform flow. Empirical evidence indicates saturation flows up to 2574 pcu/h/lane, driven by motorcycle seepage, lateral movements, clustering, and surge effects not captured by static PCU models. A mathematical framework is proposed linking these deviations to lateral efficiency, surge dynamics, dynamic equivalence, headway expansion, and geometric constraints. Future signal design should adopt performance-based, behaviour-sensitive approaches supported by calibration using simulation tools such as SIDRA and SUMO. This provides a structured basis for developing adaptive, context-specific signal design standards for heterogeneous traffic environments.

References

1. TRB, *Highway Capacity Manual (HCM)*, Transportation Research Board, Washington D.C., 2016.

2. ARRB, *Australian Road Research Report 123 (ARR123)*, Australian Road Research Board, 1991.

3. Overseas Road Note 13 (ORN13), *Guidelines for Signal Design in Developing Countries*, Transport Research Laboratory, UK, 1991.

4. Webster, F.V., Traffic Signal Settings, Road Research Technical Paper No. 39, UK, 1957.

5. Gazis, D.C. and Potts, R.B., "The Oversaturated Intersection", *Highway Research Record*, 1963.

6. Gazis, D.C., “Optimum Control of a System of Oversaturated Intersections”, *Operations Research*, 1964.

7. Gartner, N.H., Little, J.D.C. and Gabbay, H., “Optimization of Traffic Signal Settings”, *Transportation Research*, 1976.

8. Michalopoulos, P.G. and Stephanopoulos, G., “Oversaturated signal systems with queue length constraints-I: Single intersection.” *Transportation Research*, Vol. 11, No. 6, December 1977, pp. 413-421. DOI:10.1016/0041-1647(77)90006-5

9. Cheng, D., Messer, C. J., Tian, Z. Z., and Liu, J., “Modification of Webster’s Minimum Delay Cycle Length Equation Based on HCM 2000,” Texas Transportation Institute, Texas AandM University, 2000.

10. Akçelik, R., *Signalized Intersection Capacity and Delay*, ARRB Research Report, 1993.

11. Mondal, A. and Gupta, A., “Dynamic PCU Estimation for Heterogeneous Traffic”, *Transportation in Developing Economies*, 2020.

12. Perera, L. and Bandara, J.M.S.J., “Empirical Saturation Flow Rates in Sri Lanka”, *IESL Transactions*, 2018.

13. Nguyen, H. D. (2016). “Saturation flow rate analysis at signalized intersections for mixed traffic conditions in motorcycle dependent cities”. *Transportation Research Procedia*, 15, 694–708.

14. Wimalasiri, R., Jayarathne, N. and Perera, L. (2023). “Investigating the impact of motorcycles on urban traffic”. *Department of Civil Engineering, University of Moratuwa*, Sri Lanka.

15. Singh, M. K., and Rao, K. R. (2023). “Simulation of signalized intersection with non-lane-based heterogeneous traffic conditions using cellular automata”. *Transportation Research Record*: Journal of the Transportation Research Board, 2678(7), 909–930

16. Nguyen, L. X., Hanaoka, S., and Kawasaki, T. (2012). “Describing non-lane-based motorcycle movements in motorcycle-only traffic flow”. *Transportation Research Record*, 2281, 76–82.

17. Minh, C.C., Sano, K. and Nguyen, T.A., “Dynamic Lane Modeling in Motorcycle-Dominated Traffic”, *J. Transportation Eng.*, 2010.

18. Malaysian Highway Authority (LLM). (2006). *Malaysian Highway Capacity Manual (M-HCM).* Kuala Lumpur: Lembaga Lebuhraya Malaysia.

19. Chandra, Satish, et al. *Indian Highway Capacity Manual (Indo-HCM)*. CSIR-Central Road Research Institute, 2017

20. Minh, C. C., Sano, K., and Matsumoto, S. (2005). “The Speed, Flow and Headway Analyses of Motorcycle Traffic”. *Journal of the Eastern Asia Society for Transportation Studies*, **6**, 1496–1508

21. Vien, L.L., Ibrahim, W.H.W. and Mohd, A.F., 2008. “Effect of motorcycles travel behaviour on saturation flow rates at signalized intersections in Malaysia”. In: *23rd ARRB Conference: Research – Partnering with Practitioners.* 30 July–1 August 2008, Adelaide, Australia.

22. Rahman, M. M., Okura, I., and Nakamura, F**.** (2004). “Effects of rickshaws and auto-rickshaws on the capacity of urban signalized intersections”. *IATSS Research*, 28(1), 26–33

23. Purohit, S., Chattaraj, U. and Panda, M., 2014. “Experimental Study of Non-Motorized Vehicle Characteristics and its Effect on Mixed Traffic”. *International Journal for Traffic and Transport Engineering*, 4(4), pp. 425-436.DOI: 10.7708/ijtte.2014.4(4).06

24. Ahmed, K., 1999. “Modeling drivers’ acceleration and lane changing behaviour. PhD Dissertation, MIT.

25. Gerlough, D.L. and Huber, M.J., 1975. Traffic Flow Theory: A monograph. Transportation Research Board.

26. Papageorgiou, M., Diakaki, C., Dinopoulou, V., Kotsialos, A. and Wang, Y., 2003. Review of road traffic control strategies. *Proceedings of the IEEE.*

27. Jayatilleke, S. and Wickramasinghe, V. (2023). Modelling of Vehicle Lane-Changing Behaviours in the Perception of a Queue at Signalized Intersections. *Transportation in Developing Economies*, 9(1)

28. Adams, C. A., Zambang, M. A. M., and Opoku-Boahen, R. (2015). “Effects of motorcycles on saturation flow rates of mixed traffic at signalized intersections in Ghana”. *International Journal of Traffic and Transportation Engineering*

29. Chanut, S. and Leclercq, L., 2005. “Modeling traffic flow with heavy vehicles”. *Transportation Research Part B.*

30. Cuddon, B. and Ogden, K., 1992. “Heavy vehicle effects on intersection performance”. *ARRB Proceedings.*

31. Chen, X., Shao, C., and Yue, H. (2007). “Influence of Bicycle Traffic on Capacity of Typical Signalized Intersection”. Tsinghua Science and Technology, 12(2), 198-203. DOI: 10.1016/S1007-0214(07)70028-7

32. Huang, L. and Wu, J. (2004). "A study on cyclist behavior at signalized intersections". IEEE Transactions on Intelligent Transportation Systems, 5(4), 293-299. DOI: 10.1109/TITS.2004.837812

33. Herath, H.M.S. and Amarasingha, N., 2022. "Pedestrian compliance and intersection safety in Sri Lanka". *IESL Transactions.*

34. Marisamynathan, S. and Vedagiri Perumal, P., 2014. "Pedestrian behavior and signal compliance in India". *Journal of Safety Research.*

35. Tsao, S.-M. and Chu, S.-W. (1995). "A Study on Adjustment Factors for U-Turns in Left-Turn Lanes at Signalized Intersections". *Journal of Advanced Transportation*, 29(2).

36. Liu, P., Lu, J.J., Fan, J., Pernia, J.C., and Sokolow, G. (2005). "Effects of U-turns on capacities of signalized intersections". *Transportation Research Record*: Journal of the Transportation Research Board, 1920(1), 74–80.

37. Abeygunawardana, C. and Wickramasinghe, V., 2020. "Estimating the follower vehicle platoon delay due to "U" turn vehicles at centre median openings". *Department of Civil Engineering, University of Moratuwa*, Sri Lanka.

38. Schmitz, F., Wu, H., and Geistefeldt, J. (2025). "Impact of heterogeneous traffic on short-lane capacity at signalized intersections". Transportation Research Record: *Journal of the Transportation Research Board*, 2720(1), 45–58.

39. Lee, C., Hummer, J., and Rouphail, N. (2005). "Lane utilization and lane drop effects at signalized intersections". *Transportation Research Record*, 1918, 50–60.

40. Chen, P., Nakamura, H., and Asano, M. (2012). "Lane utilization analysis of shared left-turn lane based on saturation flow rate modelling". *Procedia – Social and Behavioral Sciences*, 43, 178–191.

41. Zhao, X., Yun, Y., and Yang, Q. (2013). "Capacity estimation of signalized intersections considering short lane effects". *Transportation Research Part C*: Emerging Technologies, 26, 1–14.