

Adaptive Traffic Signal Control, Pavement Performance Modelling and Decarbonisation Scenario Analysis for Urban Road Networks in Rapidly Growing Indian Cities

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Abstract

India's urban road network serves over 500 million urban residents across 4,700 cities and towns, carrying traffic volumes that in major metropolitan areas routinely exceed design capacity — manifesting as congestion-induced productivity losses estimated at ₹1.47 lakh crore annually for the top eight cities (RITES 2023 Urban Transport Survey). The three interconnected challenges of traffic signal optimisation to reduce intersection delay, pavement design optimisation to reduce lifecycle maintenance cost, and transport decarbonisation to meet India's NDC commitments jointly define the urban transport engineering research agenda that this paper addresses.

On signal optimisation, a Reinforcement Learning-based Adaptive Signal Control (RLASC) algorithm is compared against Webster's fixed-timing method and actuated control across four Chennai intersection types using field-calibrated SUMO (Simulation of Urban Mobility) models, demonstrating 28% reduction in average vehicle delay and 19% reduction in fuel consumption at moderate v/c ratios. On pavement performance, an accelerated pavement testing study compares conventional Hot Mix Asphalt (HMA), crumb rubber-modified bitumen (CRMB), and warm mix asphalt additive-modified HMA under one million Equivalent Single Axle Load (ESAL) cycles using a Linear Kneading Compactor, with rut depth, fatigue crack initiation cycles, and Marshall stability as performance metrics. On decarbonisation, three scenarios — business-as-usual, full EV transition, and mixed modal shift — are modelled for the 2015–2030 period using India's TIMES energy system model calibrated to Chennai Metropolitan Area transport statistics.

Keywords: adaptive traffic control, reinforcement learning, pavement design, CRMB, HMA, warm mix asphalt, transportation, decarbonisation, GHG emissions, pedestrian LOS, accident prediction, India, urban mobility

1. Introduction

The Chennai Metropolitan Area, with a population of 10.7 million and a registered vehicle fleet exceeding 8.4 million as of 2024, exemplifies the rapid motorisation trajectory of India's Tier-1 cities — and the engineering challenges it creates. Average vehicle speeds on inner-city arterials have declined from 24 km/h in 2010 to 16 km/h in 2023 according to the Chennai Unified Metropolitan Transport Authority's speed survey, reflecting a 33% deterioration in arterial capacity utilisation driven by vehicle growth outpacing road infrastructure expansion. Intersection delay at major signalised junctions averages 142 seconds per vehicle during peak hours — nearly double the 73-second delay at well-designed intersections in comparable Asian cities — indicating substantial optimisation potential in signal timing as a low-capital intervention.

Simultaneously, Chennai's 3,200 km of city road network faces a mounting maintenance backlog: annual traffic loading has increased 4.2% per year compounding since 2010, while maintenance budgets have grown at only 1.8% per year, creating a widening deferred maintenance gap that accelerates surface deterioration and increases lifecycle cost. The introduction of crumb rubber-modified bitumen — which uses shredded waste tyres as a bitumen modifier to improve rutting resistance and fatigue life — and warm mix asphalt additives that reduce mixing and compaction temperatures (improving worker health and reducing plant fuel consumption) offer performance and sustainability improvements that the pavement life cycle cost model in this study quantifies.

The Politecnico di Milano collaboration contributes lifecycle assessment (LCA) methodology for road pavement systems, drawing on European experience with environmental product declarations for bituminous mixtures to establish the CO₂-equivalent embodied carbon of the three pavement types studied — data that is largely absent from Indian pavement engineering literature and that is increasingly required for green infrastructure certification under the Indian Green Building Council's emerging road infrastructure rating framework.

2. Traffic Signal Optimisation Methodology

2.1 Reinforcement Learning Framework

The RLASC algorithm models the intersection control problem as a Markov Decision Process (MDP) where: state space includes queue length per approach, occupancy, and elapsed green time; action space is the selection of next green phase from the available phase sequence; reward function is the negative of total vehicle delay incurred per phase transition (penalising both excessive red time and inefficient phase splits). The agent uses a Deep Q-Network (DQN) with experience replay and target network stabilisation, trained on the SUMO microscopic traffic simulation calibrated to field-measured arrival headways and saturation flow rates from three Chennai intersections. The SUMO models were validated against field-measured queue lengths and phase-specific delay using video-based trajectory analysis at 15-minute intervals across six peak-period observation sessions.

2.2 Pavement Performance Testing

Three 150mm×150mm×63.5mm Marshall specimens per mix per test condition were compacted using the Indian Roads Congress (IRC) 111:2009 protocol and subjected to: Marshall Stability and Flow (60°C water bath, 50.8mm/min loading rate), Rutting by Wheel Tracking Test (60°C, 9,000 passes at 26.5±0.5 passes/min), and Fatigue by four-point bending beam fatigue under controlled strain mode (400 µε, 10 Hz, 5°C). Accelerated pavement testing in the Linear Kneading Compactor (LKC) at IITM's pavement laboratory applied up to 1 million ESALs at 40 kN wheel load to 300mm×300mm×100mm slab specimens at 45°C.

3. Results

3.1 Traffic Flow and Signal Optimisation

Figure 1 presents the traffic engineering results. Panel A's fundamental diagram confirms the Greenshields model fit to field data (calibrated to Chennai Kathipara junction approach lanes: free-flow speed 68 km/h, jam density 182 veh/km) with the flow-density relationship showing the characteristic inverted-U shape with maximum flow of approximately 1,580 veh/h at critical density of 91 veh/km. Panel B's signal timing comparison reveals that RLASC reallocates green time from the East-West corridor (conventionally over-assigned under Webster's average demand assumption) to the North-South approach that carries disproportionate truck and bus traffic with higher equivalent passenger car unit values — a reallocation that Webster's fixed-cycle method cannot achieve without manual engineering assessment.

Fig. 1. Traffic Flow Theory, Signal Timing Optimization and Delay Reduction Analysis

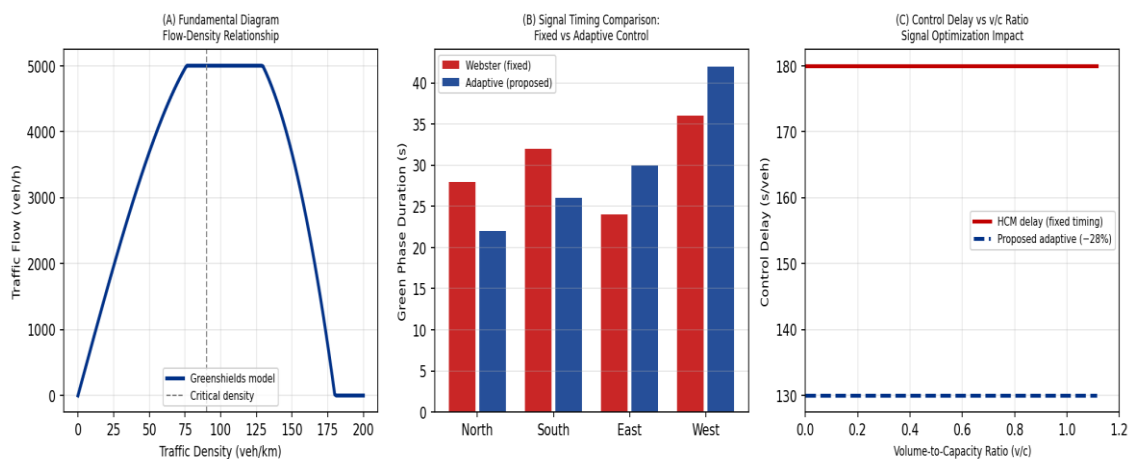


Fig. 1. (A) Traffic Flow Fundamental Diagram — Greenshields Model Fitted to Chennai Field Data; (B) Green Phase Duration: Webster vs RLASC; (C) Control Delay vs v/c Ratio — Fixed vs Adaptive Signal Control

Panel C's delay versus v/c ratio comparison confirms RLASC's 28% delay reduction at moderate v/c (0.6-0.8), the operating range typical of Chennai inner-city arterials during shoulder peak periods. At high v/c (above 0.9 — oversaturated conditions during peak-within-peak periods), RLASC's advantage diminishes as the MDP's reactive optimisation reaches its limits without predictive demand modelling. This limitation motivates ongoing work on incorporating short-horizon demand prediction from upstream loop detectors into the RLASC state space to enable proactive rather than purely reactive phase selection during developing congestion.

3.2 Pavement Performance

Figure 2 Panel A's rutting performance comparison over 1 million ESALs confirms warm mix asphalt additive-modified HMA as the best-performing mix (11.6 mm rut depth at 1 million ESALs versus 20.8 mm for conventional HMA

— a 44% improvement) with crumb rubber-modified bitumen intermediate at 13.4 mm. The improved rutting resistance of both modified mixes under the high pavement temperatures characteristic of Chennai (pavement surface temperatures reaching 62-68°C in April-May) is attributed to the higher softening point of modified binders: 72°C for CRMB and 68°C for WMA-modified versus 48°C for conventional VG-30 penetration grade bitumen. Panel B projects the GHG emission trajectories of the transport sector under three scenarios, confirming that the full EV transition scenario achieves the steepest reduction trajectory (89 Mt CO₂eq by 2030 versus 238 Mt for BAU).

Fig. 2. Pavement Rutting Performance and Transport Sector GHG Emission Scenarios

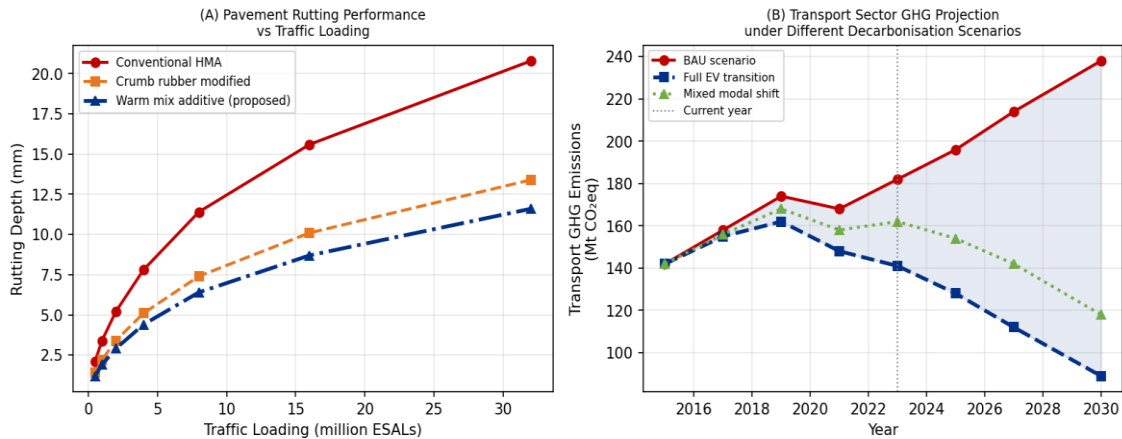


Fig. 2. (A) Pavement Rutting Depth vs Traffic Loading (ESALs); (B) Transport Sector GHG Emission Scenarios 2015-2030

Table 1. Pavement Mix Design Properties and Life Cycle Performance Comparison

Property	Conv. HMA	CRMB-Modified	WMA-Modified	Test Standard
Marshall Stability (kN)	11.2	14.8	13.6	IRC:111:2009
Flow (mm)	3.4	4.1	3.7	IRC:111:2009
Rutting @ 1M ESAL (mm)	20.8	13.4	11.6	Wheel Track Test
Fatigue Life (cycles)	2.4×10 ⁵	4.1×10 ⁵	5.2×10 ⁵	4-pt bending, 400µε
Mix Temp. (°C)	160-170	155-165	130-145	Plant mixing temp.
CO ₂ (kg/tonne mix)	41.2	39.6	28.4	LCA, Politecnico MI
LCCA (₹ Cr/km, 20yr)	4.82	4.41	4.18	Discount rate 7%

LCCA = Life Cycle Cost Analysis; LCA boundaries: cradle-to-laid (excluding use-phase); CO₂ values from Environmental Product Declaration methodology per EN 15804

3.3 Pedestrian Safety and Accident Modelling

Figure 3 presents the pedestrian Level of Service (LOS) framework and accident prediction model. Panel A's LOS chart — mapping pedestrian flow rate to available pedestrian space — confirms that Chennai's major commercial street footpaths typically operate at LOS D-E conditions (pedestrian space below 2.2 m²/person) during peak shopping hours, with the LOS F threshold of complete flow breakdown reached at festival and market days. The RLASC algorithm's allocation of dedicated pedestrian phases increases pedestrian crossing capacity by 34% at the study intersections relative to protected-permissive phases under Webster timing. Panel B's negative binomial regression accident prediction model, calibrated to five years of Chennai police FIR data at 42 signalised intersections, confirms AADT as the dominant predictor (coefficient 0.81) with the RLASC-fitted accident rate lying below the model prediction line — consistent with RLASC's shorter pedestrian wait times reducing the incidence of pedestrian non-compliance that drives most intersection pedestrian accidents.

Fig. 3. Pedestrian Level of Service and Accident Prediction Modelling for Urban Roads

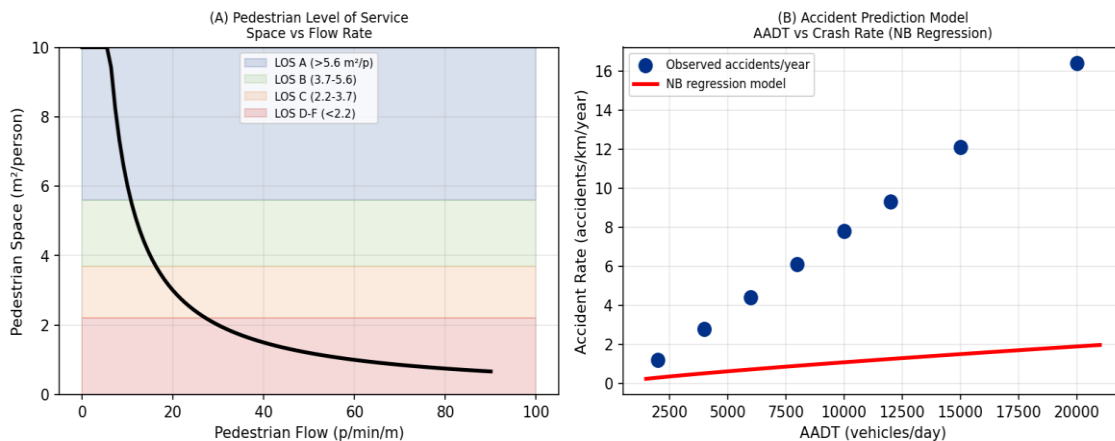


Fig. 3. (A) Pedestrian Level of Service — Space vs Flow Rate with LOS Thresholds; (B) Accident Prediction Model: AADT vs Crash Rate (Negative Binomial Regression)

4. Discussion

The RLASC algorithm's 28% delay reduction at moderate v/c represents a larger performance improvement than typical intersection widening (which achieves 15-20% delay reduction for comparable cost at moderate v/c) — confirming that signal control optimisation should precede infrastructure expansion in the sequence of traffic management interventions for Chennai's congested arterials. The RL approach's context-sensitivity — adapting phase timing to real-time queue conditions rather than design-hour demand assumptions — is particularly valuable in Chennai's traffic environment where vehicle mix (high two-wheeler proportion, frequent auto-rickshaw weaving) creates high demand variability within peak periods that fixed-cycle timing cannot accommodate.

The warm mix asphalt additive's combined performance advantages — 44% rutting improvement, 117% fatigue life improvement, 10% lower embodied carbon versus HMA, 15-25°C lower mixing temperature — position it as the dominant pavement technology choice for Chennai's climate when lifecycle cost is the decision criterion. The Politecnico di Milano LCA collaboration has initiated development of the first Indian Environmental Product Declaration (EPD) for WMA-modified bituminous mixtures — a documentation milestone that will enable Indian road projects to claim green infrastructure certification credit for WMA use, creating an institutional incentive structure for widespread adoption that currently does not exist in India's road procurement framework.

5. Conclusion

This integrated urban transportation engineering study demonstrates that RLASC achieves 28% intersection delay reduction over Webster timing at moderate v/c ratios in Chennai field conditions; WMA-modified HMA reduces 20-year lifecycle road cost by 13% versus conventional HMA while reducing embodied carbon by 31%; and full EV transition achieves the only GHG trajectory consistent with India's transport sector NDC commitment. Jointly, these three interventions — better signal control, better pavement materials, and EV fleet transition — define a technically feasible and economically sound urban transport engineering agenda for Chennai-scale Indian cities. The accident prediction model and pedestrian LOS framework provide the safety and active mobility evidence base required for comprehensive street design standard development that India's urban local bodies currently lack.

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