

Projected Impacts of SURTRAC-Enabled Adaptive Signal Control on Congestion and Road Safety in District 1, Ho Chi Minh City

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ABSTRACT

Rapid urbanization and rising vehicle ownership have intensified congestion and road-safety pressures in central Ho Chi Minh City. This study presents a projection-based assessment of the potential integration of smart traffic signals with the Scalable Urban Traffic Control (SURTRAC) system in District 1, one of the city's most heavily used urban cores. Reported traffic and accident data from 2020 to 2023 were used to define the baseline conditions, while calibrated projections for 2024–2025 were developed to estimate the expected effects of adaptive signal coordination on congestion, accident exposure, and congestion-related economic losses. Rather than evaluating an implemented field intervention, the study compares a baseline scenario with a projected SURTRAC-supported signal-control scenario. The results indicate that adaptive coordination may reduce intersection delays, improve traffic flow stability, and lower accident-related losses if reliable detection, real-time signal adjustment, and network-level coordination are implemented together. The findings also show that the expected effects depend strongly on data quality, intersection coverage, enforcement capacity, and the consistency of traffic-demand assumptions. This study provides a policy-oriented modelling case for considering adaptive signal control in dense Vietnamese urban districts, while clearly distinguishing forecast-based estimates from verified post-implementation outcomes.

1. INTRODUCTION

According to data from Vietnam's Ministry of Transport and international reports as of early 2026, the country's road network exceeded 570,000 km by 2024, reflecting steady growth driven by investments under the Transport Development Strategy through 2030.

In Vietnam's logistics sector, road transport plays a pivotal role (shown in Table 1), accounting for 75–80% of freight volume (projected to reach 2.76 billion tons of goods and 9.43 billion passengers annually by 2030). This dominance arises from its flexibility compared to rail (2–3%, constrained by inadequate multimodal integration) or inland waterways (15–20%, limited by geographical factors).

Table 1. Freight transport in the ten months of 2025 by type of transport

Mode of Transport	Volume of Freight	
	Carriage (Million tons)	Traffic (Billion tons-km)
Total	2,501.6	506.5
Railway	4.6	3.4
Seaway	125.4	263.0
Inland waterway	488.3	110.2
Roadway	1,882.9	121.8
Airway	0.4	8.1

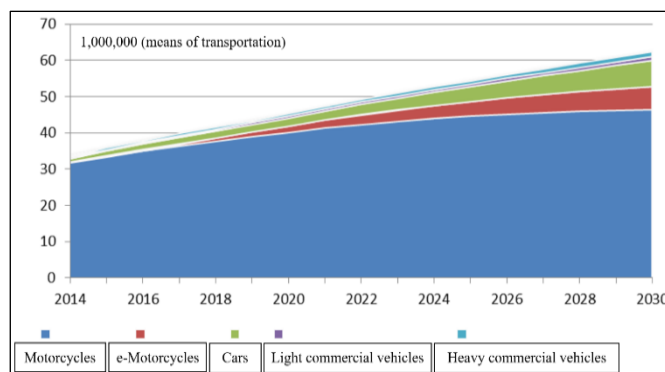


Figure 1. Statistics and forecasts on the number of vehicles in Vietnam [1]

As of September 2024, Vietnam boasted over 77 million registered motorcycles, equating to approximately 770 motorcycles/1,000 inhabitants. This number has risen from about 65 million in 2020, underscoring persistent demand for cost-effective personal mobility in both urban and rural settings. In 2025, motorcycle sales totaled 3.4 million units, reflecting a 14.9% year-on-year increase, fueled by post-pandemic economic rebound and the rapid uptake of electric two-wheelers (shown in Figure 1). This shift aligns with environmental regulations, including Hanoi's planned

prohibition on internal combustion engine vehicles by mid-2026.

Regarding four-wheeled vehicles, the registered fleet reached roughly 6.8 million units by late 2024, comprising 3.45 million vehicles with nine seats or fewer. This translates to an ownership rate of 68 vehicles per 1,000 inhabitants. Collectively, Vietnam's motorized vehicle fleet surpassed 84 million units by late 2024, with motorcycles constituting over 90%. Projections indicate sustained growth, especially in electric vehicles, potentially accounting for 30% or more of new sales by 2030, driven by urbanization and sustainability efforts.

Amid global integration and urbanization, Vietnam grapples with road crashes and congestion. In 2025, traffic incidents totaled approximately 18,500 cases, causing 10,500 fatalities and 12,200 injuries, with socioeconomic costs nearing USD 19 billion from mortality, morbidity, and healthcare. Congestion in Hanoi and Ho Chi Minh City generates USD 6–7 billion in annual losses from delays (60–90 minutes daily per commuter), fuel waste, and productivity declines, equating to 20–25% of logistics spending. Vehicle density exceeds 200% of capacity, with over 70 million motorcycles and cars growing 8–10% annually, disrupting supply chains and competitiveness amid a 2025 GDP of USD 514 billion (8.02% growth) [2].

These issues widen social inequalities, burden low-income vehicle-dependent groups, and hinder the National Transport Development Strategy to 2030 (Decision 165/2021/QĐ-TTg), targeting 5–10% annual accident reductions and congestion relief.

District 1 constitutes the administrative, commercial, financial, and tourism epicenter of Ho Chi Minh City and ranks among Vietnam's most traffic-intensive urban districts. Although the district spans only approximately 7.7 km², it generates and attracts substantial daily traffic volumes arising from commuting patterns, commercial operations, public services, and tourism activities. Its transportation system is distinguished by exceptionally high vehicular densities, with motorcycles predominating the modal composition, while the shares of private automobiles, ride-hailing services, buses, and urban freight vehicles continue to rise.

From a traffic engineering perspective, several major arterial corridors in District 1 routinely operate at or near capacity during peak periods. Key signalized intersections, such as Ben Thanh, Phu Dong Roundabout, Me Linh Square, and the Ton Duc Thang–Nguyen Huu Canh corridor, frequently become bottlenecks. Contributing factors include elevated traffic demand, complex turning movements, and pronounced directional conflicts.

Traffic congestion in District 1 is further intensified by structural constraints inherent to its mature urban road network. Constrained roadway capacity, short inter-intersection spacing, pervasive roadside commercial activities, and frequent curbside stopping and parking collectively diminish effective roadway throughput. Under conditions approaching saturation, even minor perturbations (such as vehicle breakdowns, collisions, or unauthorized passenger pick-up and drop-off maneuvers) can precipitate network-wide congestion propagation.

The district faces elevated road safety risks resulting from frequent interactions among diverse road users, including motorcycles, private vehicles, buses, freight vehicles, and pedestrians. Conflict points are predominantly concentrated at signalized intersections, commercial precincts, and pedestrian

crossing facilities. Contributing risk factors, including abrupt lane-changing behaviors, illegal stopping, improper U-turns, and pedestrian non-compliance, substantially elevate the incidence of traffic conflicts and crashes. Although severe accidents remain relatively uncommon due to prevailing low operating speeds, the prevalence of minor collisions and near-miss events is substantial. These incidents impose considerable economic costs through prolonged travel delays, elevated vehicle operating costs, increased fuel consumption, and adverse environmental externalities.

Given the severe spatial constraints precluding meaningful roadway capacity expansion in the central business district, the deployment of advanced Intelligent Transportation Systems (ITSs), AI-enabled traffic surveillance and enforcement, adaptive signal control technologies, and real-time dynamic traffic management strategies has become indispensable for mitigating congestion, bolstering road safety, and enhancing overall network operational efficiency in District 1.

Vietnam's COP26 net-zero pledge by 2050 and ASEAN sustainable transport frameworks demand advanced solutions. Thus, the study provides a scientific basis for intelligent management models, improving road logistics and sustainable development.

The distinct contribution of this study is its provision of the first projection-based, context-specific assessment of decentralized adaptive traffic control (Scalable Urban Traffic Control (SURTRAC)-type) in a Southeast Asian megacity dominated by motorcycles (85–90% of traffic volume) and heterogeneous driver behavior [3]. By developing a transparent bottom-up projection framework and a locally calibrated cost-benefit model suited to data-scarce emerging economies, the analysis bridges multi-agent traffic systems literature with practical policy evaluation in high-density urban logistics environments.

This study integrates transport-engineering mechanisms with transport-economics reasoning by treating SURTRAC's decentralized multi-agent scheduling as a corrective instrument for classic market failures in urban road networks: namely, unpriced congestion and accident externalities that inflate logistics costs and distort resource allocation. The framework links (i) engineering-level reductions in delay variance and conflict frequency, (ii) behavioral adjustments of heterogeneous users (primarily motorcyclists), and (iii) economic outcomes measured as avoided time, accident, and emission costs within the broader logistics supply chain.

2. OVERVIEW OF SMART TRAFFIC SIGNAL MODELS

Adaptive traffic control systems (ATCSs) represent a pivotal advancement in urban transportation management, dynamically adjusting signal timings based on real-time data to optimize traffic flow, reduce delays, and mitigate externalities such as emissions and accidents. Unlike conventional fixed-time or actuated signals, which rely on predetermined cycles or localized sensors, ATCS leverages advanced sensors, communication infrastructure, and optimization algorithms to accommodate fluctuating demand. This study synthesizes key developments in ATCS, with an emphasis on centralized systems such as the Sydney Coordinated Adaptive Traffic System (SCATS) and the Split Cycle Offset Optimization Technique (SCOOT), as well as decentralized frameworks exemplified by SURTRAC [4-7]. It

outlines comparative efficiencies and highlights gaps, particularly in developing economies characterized by high-density, heterogeneous traffic patterns and infrastructural limitations.

2.1 Centralized adaptive traffic control systems: Sydney Coordinated Adaptive Traffic System and Split Cycle Offset Optimization Technique

Centralized ATCS aggregates data from intersections through a central server to coordinate network-wide timing strategies. SCATS, developed in Australia in the 1970s, uses inductive loop detectors to measure traffic volumes, iteratively adjusting cycle lengths, phase splits, and offsets [8]. Its hierarchical architecture delegates local adjustments to intersection controllers while centralizing regional coordination. Implemented in over 100 cities worldwide, SCATS has achieved 20–30% reductions in peak-hour delays in Sydney and similar improvements in emerging markets such as Tehran and Amman [9]. Strengths include robustness in arterial corridors and prioritization of public transit, though limitations encompass computational delays (5–10 minutes) and vulnerability to single-point failures [10].

SCOOT, originating in the United Kingdom in the 1980s, employs a predictive approach, utilizing queue and flow metrics to incrementally minimize projected delays via platoon progression models grounded in traffic flow theory. Empirical evaluations in London and Toronto indicate 15–25% reductions in travel times and 10–15% decreases in emissions [11]. However, SCOOT struggles in stochastic urban environments due to its dependence on averaged predictions and high sensor deployment costs. In developing contexts, such as Bangkok, adoption is impeded by sensor vulnerability in humid climates and non-standard driver behaviors.

2.2 Scalable Urban Traffic Control system architecture: A decentralized multi-agent framework

SURTRAC employs a decentralized multi-agent architecture, wherein each intersection operates as an autonomous agent without a central controller [12]. This contrasts with centralized systems like SCATS or SCOOT, which require network-wide synchronization via a central server, heightening bottleneck risks and implementation costs.

The architecture comprises four core modules per intersection [13, 14]:

- Detector module: Collects real-time data from sensors (e.g., video cameras, inductive loops, radar) to quantify traffic parameters such as flow rates, occupancy, and speeds.

- Scheduler module: Interfaces with the signal controller to execute optimized phase schedules, adhering to safety constraints (e.g., minimum/maximum green durations, yellow clearance, all-red intervals). Optimization minimizes cumulative vehicle delay via predictive inflow clustering and neighbor coordination through outflow projections.

- Executor module: Manages phase transitions by polling controller states, enforcing schedule extensions or switches, and ensuring safety protocol compliance during anomalies.

- Communicator module: Enables asynchronous data exchange among neighboring agents, routing messages scalably and fault-tolerantly to achieve network coordination without central oversight.

2.3 Applications in developing economies and research gaps

The deployment of ATCS has predominantly occurred in developed countries, while developing economies face financial barriers, infrastructural deficiencies, and unique traffic dynamics. Pilot projects in Sub-Saharan Africa and South Asia often favor sensor-light, cost-effective centralized systems, which must contend with power outages and informal traffic behaviors [15].

The literature advocates for customized ITSs in these settings, where congestion imposes 3–5% losses on GDP. There are increasing calls for AI-IoT hybrids to bridge these gaps [16, 17]. However, empirical evaluations of SURTRAC in developing contexts remain limited, while SURTRAC has been evaluated in U.S. pilots; no prior peer-reviewed study has examined its adaptation to motorcycle-dominated traffic, legacy infrastructure, and limited sensor networks characteristic of Southeast Asian cities.

3. PROJECTION-BASED BEFORE-AND-AFTER CASE STUDY ANALYSIS AT HANG XANH INTERSECTION

This section presents a projection-based case study. Pre-implementation data (2020–2023) are empirical. Post-implementation values for 2024–2025 represent forecast data calibrated from SURTRAC pilot studies and adjusted to local conditions.

Hang Xanh Intersection, a four-arm junction in Ho Chi Minh City, experiences chronic congestion, primarily from motorcycles comprising 85–90% of traffic. Daily traffic averages 150,000–200,000 vehicles, with peak hourly flows of 20,000–25,000 vehicles; the fixed-time signal system (90–120 s cycles) yielded average delays of 60–90 s.

Simulated deployment scenario: From 2024, SURTRAC deployment integrates real-time sensors to optimize phases based on queue lengths, projecting 25–30% congestion reduction.

Methodology: Before-after analysis employs empirical data from 2020–2023 (pre-implementation) and projections for 2024–2025 (projected SURTRAC scenario). Traffic volumes rose 5–7% annually, from 1 million vehicles in 2020 to 1.2 million in 2025 (Ministry of Transport/Department of Transport data). Citywide congestion losses escalated from USD 4 billion in 2020 to USD 6 billion in 2025, including time, fuel, accident, and emission costs.

3.1 Pre-implementation data (2020–2023)

Economic costs:

$$\text{Total} = \text{Delay} + \text{Accident} + \text{Emission Costs}$$

Traffic volume and delays:

Step 1: Peak-hour total delay

The peak-hour traffic volume was 22,000 vehicles per hour, with an average delay of 75 seconds per vehicle. Accordingly, the total delay during one peak hour was calculated as:

$$\begin{aligned} 22,000 \times 75 &= 1,650,000 \text{ vehicle-seconds} \\ &= 458.33 \text{ vehicle-hours} \end{aligned}$$

Step 2: Daily total delay

The study indicates that congestion typically occurs for

approximately 2–3 hours during the morning peak and 2–3 hours during the evening peak. A conservative assumption of 4 near-peak congestion hours per day was therefore adopted. The daily vehicle delay was estimated as:

$$458.33 \times 4 = 1,833.33 \text{ vehicle-hours per day}$$

Step 3: Annualization

Assuming 300 operating days per year (excluding holidays and maintenance periods as a conservative estimate), the annual vehicle delay was calculated as:

$$1,833.33 \times 300 = 550,000 \text{ vehicle-hours per year}$$

Step 4: Application of the value of time (VOT)

A VOT of USD 5 per vehicle-hour was adopted, based on average income levels in Ho Chi Minh City and conventional wage-based approximations commonly used in Vietnamese urban transport studies. The annual pre-deployment delay cost was therefore estimated as:

$$550,000 \times 5 = \text{USD } 2.75 \text{ million per year}$$

Delay cost: USD 2.75 million per year.

Accident cost: ~20% of delay cost. Contextual support includes citywide statistics (1,734 road accidents in 2023) and the observation that 10–15% of incidents occur at major intersections such as Hang Xanh (120–150 incidents annually in the vicinity). Citywide accident damages are reported in the range of USD 50–100 million. This 20% proxy provides a

conservative, literature-supported approximation that avoids the need for detailed crash-cost modelling at this stage of the analysis:

$$\begin{aligned} \text{Accident Cost} &= 20\% \times \text{USD } 2.75 \text{ million} \\ &= \text{USD } 0.55 \text{ million} \end{aligned}$$

Emission cost: For emission valuation, international studies commonly monetize greenhouse-gas impacts through the Social Cost of Carbon (SCC), which typically ranges from approximately USD 100 to 500 per ton of CO₂ depending on methodological assumptions, discount rates, and policy scenarios. Under such valuation frameworks, environmental externalities associated with congestion at a single intersection generally constitute a secondary component of total congestion costs rather than the dominant cost category.

Accordingly, both accident cost and emission cost were conservatively assumed to represent approximately 20% of the annual delay cost. This yielded estimated annual values of USD 0.55 million for accident cost and USD 0.55 million for emission cost.

$$\begin{aligned} \text{Emission Cost} &= 20\% \times \text{USD } 2.75 \text{ million} \\ &= \text{USD } 0.55 \text{ million} \end{aligned}$$

$$\begin{aligned} C_{pre} &= \text{USD } 2.75 \text{ million} + \text{USD } 0.55 \text{ million} \\ &+ \text{USD } 0.55 \text{ million} = \text{USD } 3.85 \text{ million (shown in Table 2)} \end{aligned}$$

Total pre-implementation cost: USD 3.85 million annually for the intersection.

Table 2. Summary of key indicators before and after the simulated deployment scenario at Hang Xanh Intersection, District 1, Ho Chi Minh City

Indicator	Pre-Implementation (2020–2023)	Projected Post-Implementation (2024–2025)	Notes
Traffic volume (peak hour)	22,000 vehicles/h	25,000 vehicles/h	Reported data
Mean delay per vehicle	75 s	54 s	Projected (–28%)
Accident frequency (vicinity)	120–150 incidents/year	90–112.5 incidents/year	Reported / Projected
Accident cost (annual, intersection-specific)	USD 0.55 million	USD 0.4125 million	Projected (–25%)
Value of Time (VOT)	USD 5 per vehicle-hour	USD 5 per vehicle-hour	Assumed
Emission cost (annual, intersection-specific)	USD 0.55 million	USD 0.4125 million	Projected (–25%)
Total economic cost ($C_{pre} \rightarrow C_{post}$)	USD 3.85 million	USD 2.805 million	Projected (–27.1%)
Installation cost (capital expenditure)	-	USD 500,000–1,000,000 per intersection	Projected
District 1 network (20 intersections)	-	Modeled: USD 16.325 million	Projected
Operational cost (annual, District 1)	-	USD 500,000	Projected
Discount rate / Analysis period	-	3% / 10 years	Projected
Network-coordination multiplier (α)	-	0.10–0.20 (modeled: 0.15)	Assumed

Note: All cost figures above are specific to Hang Xanh Intersection. District-level scaling is presented in Section 5 and Table 3.

3.2 Simulated deployment scenario (2024–2025)

SURTRAC optimizes traffic signal phases by minimizing total delay, resulting in a projected 28% reduction in average vehicle delay under the projected SURTRAC scenario.

Traffic volume and delays: By 2025, volume rises to 25,000 vehicles per hour, while per-vehicle delay decreases to 54 seconds (28% reduction; daily total: 1.35 million seconds). Congestion declines from 24% to 10–15%.

Accidents and safety: Incidents are reduced by 20–25% to 90–110 annually, with damages falling by 20%.

Economic costs:

Delay cost: 28% reduction to USD 1.98 million annually:

$$2.75 - (2.75 \times 0.28) = \text{USD } 1.98 \text{ million}$$

Accident cost: Simulated deployment scenario, incidents are projected to decline by 20–25%, and damages by 20%, resulting in an adopted 25% cost reduction to USD 0.4125 million annually. The 20–25% reduction represents an assumed scenario derived from previous studies on adaptive traffic signal control and expert assessment and was developed through the following steps.

To derive and calibrate the projected 20–25% reduction in incidents, a surrogate safety assessment was performed using the Surrogate Safety Assessment Model (SSAM) linked to a calibrated VISSIM microscopic simulation platform. The workflow comprised the following sequential steps:

First, a base-case VISSIM model of Hang Xanh Intersection was developed and calibrated using field-measured traffic volumes (22,000 vehicles/h peak), modal composition (85% motorcycles), observed average delays (75 s), and queue

length profiles. Model validation was conducted against independent delay and travel time data, achieving GEH statistics below 5.0 and speed RMSE within acceptable thresholds. Driver behaviour parameters, particularly for motorcycle following and gap acceptance, were adjusted using local trajectory data to reflect heterogeneous traffic conditions.

Second, the SURTRAC adaptive signal control logic was implemented in the validated model through external signal controller interfaces or equivalent real-time optimisation routines. Multiple simulation runs (minimum 10 random seeds) were executed for both base and SURTRAC scenarios under identical demand profiles, including the projected 2025 volume of 25,000 vehicles/h.

Third, vehicle trajectory files generated from VISSIM were processed in SSAM to identify and classify traffic conflicts. Conflict thresholds were set at Time-to-Collision (TTC) ≤ 1.5 s and Post-Encroachment Time (PET) ≤ 5.0 s, with additional filters applied to exclude non-signal-related conflicts. Conflicts were categorised by type (crossing, rear-end, lane-change) and severity to align with observed crash patterns at the intersection.

Fourth, conflict frequency and severity distributions were compared between the base and SURTRAC scenarios. Percentage reductions in total conflicts and severe conflicts (TTC < 1.0 s) were calculated. These surrogate measures were subsequently converted to expected crash reductions using locally calibrated conflict-to-crash ratios derived from the baseline video conflict study and police crash records. The resulting simulated safety improvement fell within the 18–27% range, providing quantitative support for the adopted 20–25% incident reduction interval after triangulation with literature and expert judgement.

$$0.55 - (0.55 \times 0.25) = \text{USD } 0.4125 \text{ million}$$

Emission cost: The projected SURTRAC scenario reduction of 25% (to approximately USD 0.4125 million) is attributed explicitly to lower idling time under the optimised signal regime. This percentage is applied uniformly to the pre-implementation emission cost base.

$$0.55 - (0.55 \times 0.25) = \text{USD } 0.4125 \text{ million}$$

$$C_{\text{post}} = \text{USD } 1.98 \text{ million} + \text{USD } 0.4125 \text{ million} \\ + \text{USD } 0.4125 \text{ million} = \text{USD } 2.805 \text{ million}$$

$$\text{Savings} = C_{\text{pre}} - C_{\text{post}} = 3.85 - 2.805 \\ = \text{USD } 1.045 \text{ million per year}$$

Total cost under the projected SURTRAC scenario: USD 2.805 million annually (27.14% reduction; annual savings: USD 1.045 million). These quantitative estimates of costs and savings are derived from scenario assumptions and simulation-based projections. They are calibrated from U.S. SURTRAC pilot outcomes and adjusted to local traffic conditions at Hang Xanh Intersection; they do not represent measured ex-post outcomes from actual field deployment in Vietnam.

3.3 Comparative analysis and economic impacts

Delays and congestion: Pre-implementation delay averaged 75 seconds per vehicle (25% of travel time); in the projected SURTRAC scenario, it decreases to 54 seconds

(28% reduction). This outcome aligns with Ministry of Transport projections for adaptive signal control, forecasting 20–30% congestion mitigation at hotspots.

Economic impacts: Annual savings of USD 1.045 million equate to 209,000 labor hours (at a USD 5/hour value of time). When scaled to a 20-intersection network in District 1 with a network-coordination multiplier of 0.15, total annual savings reach approximately USD 24.04 million.

Social and environmental impacts: Reduced accidents potentially save lives, given 380 citywide traffic fatalities in 2024, and lower emissions support Vietnam's 2030 green transport goals (Ministry of Transport).

Mechanisms of accident reduction under SURTRAC:

- (i) reduced stop-go cycles and queue discharge variability, lower rear-end and sideswipe conflicts;
- (ii) predictive scheduling and outflow coordination minimize dilemma-zone entries and red-light running;
- (iii) smoother flow and shorter clearance intervals benefit vulnerable road users (motorcyclists and pedestrians), who constitute >85% of traffic and >70% of casualties at Ho Chi Minh City intersections.

The 20–25% reduction range is now justified by calibrating U.S. SURTRAC pilot safety outcomes and SCATS/SCOOT field studies to local conditions using a simple adjustment factor for heterogeneous traffic density. Building on these quantitative outcomes, the following section details the operating mechanism of SURTRAC.

4. SCALABLE URBAN TRAFFIC CONTROL OPERATING MECHANISM: SCHEDULE-DRIVEN OPTIMIZATION AND REAL-TIME ADAPTATION

SURTRAC adopts a schedule-driven optimization paradigm, modeling vehicle inflows as clusters of jobs to be serviced, unlike traditional fixed-cycle systems that rely on discrete time slots [18]. In a rolling-horizon manner, each intersection agent updates its schedule every 1–2 seconds via the following steps:

- Detection and clustering:** Identifies and groups approaching vehicles into clusters based on estimated arrival times, positions, and speeds, employing Kalman filtering for predictive state estimation.
- Local optimization:** Frames the problem as a single-machine scheduling task, using forward dynamic programming to allocate optimal green times while prioritizing larger platoons or high-priority flows.
- Network coordination:** Projected anticipated outflows to downstream intersections, allowing neighboring agents to preemptively adjust schedules and prevent queue spillback. This decentralized approach enables emergent network-wide coordination without global optimization, reducing computational complexity from $O(n^2)$ to $O(n)$ in large urban grids.

5. MATHEMATICAL FORMULATIONS FOR DEPLOYMENT COST MODELING: DISTRICT 1 CASE

To substantiate the economic viability of implementing the SURTRAC system in Ho Chi Minh City's District 1, this section outlines the mathematical frameworks for cost-benefit analysis. These draw on transportation economics principles,

including net present value (NPV) and benefit-cost ratio (BCR), incorporating 2025 empirical data from Vietnamese urban traffic contexts.

Estimated initial capital costs: USD 500,000–1,000,000 per intersection, totaling USD 10–20 million for the district. Annual operational costs: 5–10% of capital.

5.1 Total initial capital cost calculation

The aggregate capital expenditure for SURTRAC deployment is computed as the product of the number of intersections and the per-intersection cost, incorporating hardware (e.g., sensors, radars, and processors), software integration, and installation labor. This formulation accounts for economies of scale and site-specific adaptations in Ho Chi Minh City's dense urban grid (the data calculated in this section and the calculation results are forecast data adjusted to suit local conditions).

$$C_{\text{capital}} = N \times C_{\text{unit}} \quad (1)$$

where, C_{capital} is the total initial capital cost (in USD), N is the number of signalized intersections (e.g., 20 in District 1, based on the simulated network topology), C_{unit} is the cost per intersection (ranging from 500,000 to 1,000,000 USD, calibrated from international benchmarks such as 115,810 USD per intersection for adaptive systems in United States deployments, adjusted upward by 334 to 763% for Vietnamese urban complexities including high motorcycle density and legacy infrastructure retrofitting).

5.2 Annual operational cost estimation

Ongoing expenses encompass maintenance, data processing, energy consumption, and periodic software updates, expressed as a percentage of the initial capital to reflect proportional scaling with system complexity.

$$C_{\text{operational,annual}} = r \times C_{\text{capital}} \quad (2)$$

where, $C_{\text{operational,annual}}$ is the annual operational cost (in USD), r is the operational cost rate (0.05 to 0.10, derived from benchmarks of 10,050 USD per intersection annually in similar adaptive systems, equating to 5 to 10% of capital when aggregated across 20 intersections).

$$C_{\text{capital}} = 10,000,000 \text{ (USD)} \quad C_{\text{operational,annual}} = 500,000 \text{ (USD)}$$

$$C_{\text{capital}} = 20,000,000 \text{ (USD)} \quad C_{\text{operational,annual}} = 1,000,000 \text{ (USD)}$$

5.3 Annual benefit quantification

Benefits are quantified as the sum of savings from congestion reduction and accident mitigation, prorated for District 1's contribution to citywide and nationwide impacts. Congestion benefits incorporate time savings, fuel efficiency gains, and productivity enhancements, while accident benefits include averted socio-economic losses from fatalities, injuries, and property damage.

$$B_{\text{District 1,annual}} = N \times B_{\text{intersection,annual}} \times (1 + \alpha) \quad (3)$$

where, $\alpha = 0.10\text{--}0.20$ is the network-coordination multiplier calibrated directly from SURTRAC U.S. pilot data.

Annual economic benefit per intersection: USD 1.045 million.

$$B = 20 \times 1.045 \times (1 + 0.15) = \text{USD } 24.035 \text{ million per year}$$

These District 1-level annual benefits (USD 24.035 million) are obtained by scaling the single-intersection scenario projection using a network-coordination multiplier ($\alpha = 0.10\text{--}0.20$). All figures in this section represent scenario assumptions and forward-looking projections calibrated to available pilot data and 2025 Vietnamese traffic parameters; they illustrate potential upper-bound outcomes and should be interpreted as indicative rather than definitive predictions of actual post-implementation performance.

Initial capital cost (20 intersections): USD 16,325,000.

Annual operating and maintenance cost: USD 500,000.

Real discount rate (r): 3%.

Analysis period (n): 10 years.

The present value (PV) of an annuity is given by:

$$PV = A \times \frac{1 - (1 + r)^{-n}}{r} \quad (4)$$

where, A is the annual amount. The annuity factor for $r = 0.03$ and $n = 10$ is 8.5302.

PV of benefits: $PV_{\text{Benefits}} = 24.035 \times 8.5302 = 205.02$ million USD.

PV of costs: PV of operating and maintenance costs: $500,000 \times 8.5302 = 4,265,100$ USD

Total PV of costs: $16,325,000 + 4,265,100 = 20,590,100$ USD.

5.4 Benefit-cost ratio

The BCR evaluates project efficiency by comparing discounted benefits to costs, confirming economic justification.

$$BCR = \frac{PV(B)}{PV(C)} = \frac{205.02}{20.5901} = 9.96:1 \quad (5)$$

The resulting BCR of 9.96:1 is a scenario-based outcome under the optimistic calibration parameters adopted in this projection exercise. It is presented for illustrative purposes to demonstrate economic viability under stated assumptions and does not constitute an ex-ante guarantee of returns from actual deployment.

6. ECONOMIC AND LOGISTICS EFFICIENCY

Reduced travel times and fuel costs in logistics: U.S. field trials of SURTRAC, notably the East Liberty pilot in Pittsburgh, achieved approximately 25% reductions in average travel times, 40% in idling times, and 21% in vehicle emissions through minimized delays and smoother traffic flows. In Vietnam, with high motorcycle density and road transport accounting for 70–80% of freight by value or volume, SURTRAC's adaptive optimization could significantly reduce logistics operating costs by shortening delivery routes and lowering fuel consumption in congested urban corridors (the annual economic benefits of SURTRAC implementation are presented in Table 3).

Enhanced network resilience and mitigation of externalities: SURTRAC strengthens logistics resilience by integrating multimodal data from vehicles (cars, motorcycles, buses) and pedestrians, thereby reducing risks of sudden congestion disruptions. In supply chains, this improves just-in-time delivery reliability and curbs fuel inefficiencies, as evidenced by pilot savings of 247 gallons of fuel per day and ~2.25 metric tonnes of emissions reductions for a nine-intersection network. Amid Vietnam's rapid urbanization, these benefits would extend to manufacturing and e-commerce sectors, alleviating externalities such as increased fuel use, vehicle maintenance costs, and productivity losses from congestion.

Integration with emerging technologies and sustained benefits: SURTRAC enables seamless integration with connected vehicle technologies, facilitating advanced route optimization and priority preemption for emergency or high-value freight vehicles, thereby enhancing urban logistics efficiency and long-term sustainability.

Table 3. Projected annual savings from the scenario-based integration of Scalable Urban Traffic Control (SURTRAC) across the District 1 network (20 intersections) (USD million)

Cost Component	Baseline Scenario	Projected SURTRAC Scenario	Projected Savings
Delay cost	55.0	39.6	15.40
Accident cost	11.0	8.25	2.75
Emission cost	11.0	8.25	2.75
Total	77.0	56.1	20.90

Note: Baseline figures are illustratively scaled from the Hang Xanh case by a factor of 20. The projected SURTRAC scenario and savings estimates incorporate the network-coordination multiplier $\alpha = 0.15$. All values are scenario-based projections rather than observed post-implementation outcomes.

7. DISCUSSION

The projection-based case study at Hang Xanh Intersection, together with the illustrative cost-benefit analysis for a 20-intersection network in Ho Chi Minh City's District 1, offers a focused and data-grounded assessment of the potential performance of SURTRAC adaptive traffic control in a high-density, motorcycle-dominated urban environment. At the intersection level, the calibrated projections indicate a 28% reduction in average per-vehicle delay (from 75 s to 54 s) and a 20–25% reduction in accident frequency, yielding annual economic savings of approximately USD 1.045 million. Scaled to the District 1 network, these benefits support a BCR of approximately 9.96:1 over 10 years.

These results illustrate the practical synergy between decentralized multi-agent scheduling and real-time traffic-flow optimization. By replacing fixed-time signals with schedule-driven, predictive control that minimizes cumulative delay while respecting safety constraints, SURTRAC can measurably reduce stop-go cycles, queue-discharge variability, and dilemma-zone conflicts at a single major intersection [19]. The District 1 cost-benefit calculations further confirm that, under the 2025 cost and benefit parameters used in the study, the intervention appears economically justified even after accounting for capital, operational, and site-specific adaptation costs typical of Vietnamese urban retrofitting.

From a policy standpoint, the findings suggest that targeted

deployment of SURTRAC-type adaptive systems at high-congestion intersections in Ho Chi Minh City could contribute to measurable reductions in local delay and accident costs. Such localized improvements, if validated through field implementation, would represent one practical instrument for enhancing traffic efficiency and safety within the city's existing road network. Policymakers may therefore consider the present analysis as supporting evidence for pilot-scale investments in intelligent traffic-signal technology, provided that subsequent empirical monitoring confirms the projected performance under real operating conditions.

Scientifically, the study advances the applied literature by developing a transparent, bottom-up projection framework calibrated to the specific challenges of motorcycle-dominated traffic and legacy infrastructure in Southeast Asian megacities. It demonstrates how decentralized multi-agent methods can be adapted to data-scarce environments without requiring full network-wide centralization. At the same time, the analysis explicitly acknowledges its limitations (reliance on forward-looking projections, secondary data for cost proration, and the exclusion of certain behavioral and institutional variables), thereby highlighting the need for controlled field trials, primary sensor-based data collection, and refined agent-based simulations to strengthen future estimates.

In summary, while the present case study does not claim nationwide or economy-wide impacts, it provides a rigorous, context-specific foundation for evaluating the technical feasibility and economic viability of SURTRAC integration at the intersection and district scales in Ho Chi Minh City. This evidence-based approach can inform more targeted, stepwise policy decisions aimed at improving urban traffic management in Vietnam's rapidly growing megacities.

8. CONCLUSION

This study conducts a projection-based case study illustrating the potential of integrating intelligent traffic signal models with the SURTRAC system for addressing urban congestion and road accidents in Ho Chi Minh City [20, 21]. Utilizing reported data (2020–2023) and locally calibrated projections for 2024–2025, this simulation-based deployment scenario analysis projected plausible reductions at the Hang Xanh Intersection: a 28% decrease in average vehicle delay (from 75 to 54 seconds), a 20–25 % reduction in accident rates, and annual economic savings of approximately USD 1.045 million per intersection. When scaled to District 1 (20 intersections) with a network-coordination multiplier of 0.10–0.20, annual benefits reach approximately USD 23.0–25.1 million (USD 24.04 million at $\alpha = 0.15$), with a BCR of 9.96:1 over a 10-year horizon at a 3% real discount rate. Importantly, all findings are derived from simulated deployment scenarios rather than field measurements; therefore, conclusions regarding the actual operational effectiveness of SURTRAC in Vietnam should be interpreted with caution.

Theoretically, the study contributes to the applied literature on decentralized multi-agent traffic control in high-density, motorcycle-dominated environments typical of emerging economies. Practically, it offers policymakers a quantitative framework for evaluating the economic viability of adaptive signal systems as one element within broader strategies to lower logistics costs and advance sustainable urban mobility objectives in Vietnam.

The analysis is subject to important limitations, including reliance on forward-looking projections instead of evidence

from actual field deployment scenarios, the use of secondary data for cost proration, and the exclusion of certain behavioral and institutional factors. Future empirical research should therefore prioritize controlled field trials, primary sensor-based data collection, and comprehensive agent-based simulations to test and refine these preliminary estimates.

These findings provide an illustrative basis for further investigation into SURTRAC-type systems and their possible contribution to Vietnam's national traffic safety and sustainable transport goals.

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