



Research Paper

Mathematical Analysis of Traffic Flow Models for Urban Congestion: Review of Macroscopic and Microscopic Approaches with Simulations for Thai Nguyen City

Le Bich Ngoc

Thai Nguyen University of Technology

Abstract

Urban congestion poses significant challenges in rapidly industrializing cities, particularly in mid-sized hubs like Thai Nguyen City, Vietnam, where mixed traffic, motorbike dominance, and factory-driven peak flows strain limited infrastructure. This paper reviews macroscopic traffic flow models (LWR, Payne-Whitham, Aw-Raschle-Zhang) and microscopic approaches (car-following models such as IDM, cellular automata like NaSch), comparing their theoretical foundations, computational efficiency, scalability, and ability to capture congestion dynamics. Macroscopic models offer efficient network-level analysis, while microscopic models provide a detailed representation of heterogeneous behavior and emergent phenomena. Simulations using realistic Thai Nguyen traffic data (vehicle composition, peak-hour demand, road geometry) demonstrate both approaches' strengths in reproducing observed patterns—queue lengths, travel times, and stop-and-go waves. The study highlights the complementary use of macro for planning and micro for bottleneck analysis, offering practical recommendations for congestion management in similar Vietnamese industrial cities.

Keywords: traffic flow models, macroscopic models, microscopic models, urban congestion, Thai Nguyen City, mixed traffic, simulation analysis, congestion management.

I. Introduction

Urban congestion has become a pressing challenge in rapidly developing countries, driven by the interplay of fast urbanization, population growth, and rising vehicle ownership. This issue is particularly pronounced in Vietnam, where motorbikes dominate over 70% of the vehicle population, and inadequate infrastructure exacerbates delays in urban and industrial zones. Rapid industrialization further compounds traffic challenges, with major cities like Hanoi and Ho Chi Minh City experiencing economic losses equivalent to 1.2–1.5% of GDP due to congestion. Peak-hour speeds frequently drop below 15–20 km/h in central districts, a situation worsened by surging private vehicle ownership—car numbers are growing at an annual rate of 10–15%—and heavy commuting to industrial zones. These dynamics not only strain road networks but also contribute to rising emissions and declining urban livability. Thai Nguyen City exemplifies these trends as a mid-sized industrial hub in northern Vietnam. With a population exceeding 1.2 million (2025 estimates) and significant growth propelled by manufacturing clusters such as Samsung factories in the Yen Binh and Pho Yen districts, the city faces intense commuter traffic on a daily basis. Samsung's workforce alone, comprising tens of thousands of employees, contributes to heavy inbound and outbound flows along major routes like National Highway 3 (QL3) and internal industrial roads. However, the city's road infrastructure remains insufficient; key arterials are often limited to two lanes with poor signalization. Combined with mixed traffic conditions involving motorbikes, cars, and trucks, the city regularly experiences bottlenecks during morning and evening peak hours around industrial shift changes. Recent local reports reveal a 30–50% increase in average travel times on major corridors, with intersection queues often stretching over 500 meters. Mathematical traffic flow models provide valuable tools for analyzing and managing urban congestion. Macroscopic models treat traffic as a continuous flow—akin to fluid dynamics—enabling efficient network-wide analysis. On the other hand, microscopic models explore individual vehicle behaviors and interactions, highlighting dynamic phenomena like stop-and-go waves. These models facilitate scenario simulations, solution evaluation (e.g., lane expansions, signal optimization), and cost-effective urban planning. Nonetheless, the majority of existing studies focus either on global megacities such as Hanoi and Ho Chi Minh City or on developed countries. This leaves a gap in understanding mid-sized industrial cities in Vietnam, such as Thai Nguyen, which face unique traffic patterns characterized by motorbike predominance, factory-centered commuting flows, and mixed-traffic conditions. The core research problem lies in the limited application of localized mathematical modeling—using both macroscopic and microscopic

frameworks—tailored to the specific needs of mid-sized industrial cities in Vietnam. Although global literature offers robust theoretical bases for traffic modeling, adaptation to local contexts is insufficiently addressed. Untapped variables like high motorbike usage, non-standard driving behavior, and industry-driven commuting patterns have hindered evidence-based traffic management in these cities. This study aims to address this gap through the following objectives: -Review key macroscopic (e.g., LWR, Payne-Whitham) and microscopic (e.g., car-following models, cellular automata) traffic flow models. -Assess their respective strengths, limitations, and applicability to mixed urban-industrial traffic scenarios. -Simulate select models using realistic traffic data from Thai Nguyen City to analyze its unique congestion patterns. -Propose actionable recommendations for more effective traffic management and infrastructure planning. The scope focuses on macroscopic models such as the LWR (Lighthill-Whitham-Richards) model for system-wide flow analysis and the Payne-Whitham approach for second-order dynamics. It also includes microscopic strategies like the Intelligent Driver Model (IDM) for car-following behavior and Nagel-Schreckenberg's cellular automata for discrete traffic simulations. Realistic datasets—comprising vehicle counts, travel speeds, and road geometries from Thai Nguyen—serve as input for simulation frameworks. The methodology integrates a systematic literature review from databases like Scopus, Web of Science, and IEEE Xplore with mathematical and numerical simulations. Tools such as MATLAB will solve partial differential equations for macroscopic analyses alongside SUMO or Python's TraCI library for microscopic modeling.

II. Literature review: macroscopic and microscopic traffic flow models

Mathematical traffic flow models provide essential tools for analyzing, predicting, and managing urban congestion. They are broadly classified into macroscopic and microscopic approaches, each offering distinct perspectives on traffic dynamics. Macroscopic models treat traffic as a continuum, similar to fluid flow, while microscopic models focus on individual vehicle behavior and interactions. This section reviews the fundamentals, key extensions, applications, strengths, limitations, and seminal works of both categories, with relevance to mixed traffic conditions typical of Vietnamese industrial cities like Thai Nguyen.

Macroscopic traffic flow models

Macroscopic models describe traffic at an aggregate level using continuous variables: density (k , vehicles per kilometer), flow (q , vehicles per hour), and speed (v , km/h). The foundational work is the **Lighthill-Whitham-Richards (LWR) model** (Lighthill & Whitham, 1955; Richards, 1956), which is based on the conservation law:

$$\partial k / \partial t + \partial q / \partial x = 0,$$

where $q = k \cdot v(k)$ is defined by a fundamental diagram (flow-density relationship). The fundamental diagram is typically a parabolic or triangular function, with maximum flow (capacity) at critical density and zero flow at jam density. The LWR model effectively captures shockwaves (sudden density jumps) and rarefaction waves, making it suitable for analyzing congestion propagation from bottlenecks, signalized intersections, or on-ramps. Extensions to the LWR model address its first-order limitation (no explicit velocity dynamics).

The **Payne-Whitham model** (Payne, 1971) introduces a second-order equation for velocity:

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} = - \left(\frac{1}{\tau} \right) (v - v_e(k)) - \left(\frac{c}{k} \right) \frac{\partial k}{\partial x},$$

where τ is relaxation time, $v_e(k)$ is equilibrium speed, and c is anticipation coefficient. This model captures acceleration/deceleration and stop-and-go waves more realistically. The **Aw-Rasche-Zhang (ARZ) model** (Aw & Rasche, 2000; Zhang, 2002) further improves anisotropic behavior by replacing the anticipation term with a velocity-dependent pressure term, ensuring realistic wave propagation directions and eliminating backward traveling waves.

Applications of macroscopic models include congestion shockwave analysis, bottleneck modeling, ramp metering, and large-scale network simulation. Their primary strengths are computational efficiency and scalability, making them ideal for city-wide or regional planning. Limitations include oversimplification of driver behavior, inability to capture stop-and-go waves accurately, and poor performance in heterogeneous traffic (e.g., motorbikes vs. cars in Vietnam).

Microscopic Traffic Flow Models

Microscopic models describe traffic at the individual vehicle level, focusing on car-following, lane-changing, and interaction rules. Car-following models assume each vehicle adjusts its speed based on the preceding vehicle. The Gipps model (Gipps, 1981) is rule-based, considering safe following distance and desired speed. The Intelligent Driver Model (IDM) (Treiber et al., 2000) is continuous and widely used:

$$\frac{dv}{dt} = a \left[1 - \left(\frac{v}{v_0} \right)^\delta - \left(s^* - \frac{s}{s} \right)^2 \right],$$

where s^* is desired dynamic gap, incorporating comfortable deceleration and reaction time. The Optimal Velocity Model (OVM) (Bando et al., 1995) relates acceleration to the difference between current speed and optimal velocity based on spacing.

Cellular automata (CA) models discretize space and time, with the Nagel-Schreckenberg (NaSch) model (Nagel & Schreckenberg, 1992) as the classic single-lane version: vehicles accelerate, decelerate to avoid collisions, and randomize speed with probability p . Multi-lane extensions incorporate lane-changing rules. The MOBIL model (Kesting et al., 2007) provides a lane-changing framework based on incentive and safety criteria. Microscopic models excel in capturing detailed driver behavior, heterogeneity (e.g., car vs. motorbike in Vietnam), and emergent phenomena (phantom jams, hysteresis). Strengths include realism in mixed traffic and ability to model intersections, signals, and aggressive driving. Limitations are high computational cost and the need for extensive parameter calibration, which can be challenging with limited local data.

Comparison and relevance to Thai Nguyen

Macroscopic models are efficient for network-level analysis and planning in large areas but struggle with heterogeneous traffic and detailed local dynamics. Microscopic models provide high fidelity for intersection or bottleneck studies but are computationally intensive. In Vietnamese mid-sized industrial cities like Thai Nguyen, where motorbike dominance, mixed flow, and factory-driven peaks prevail, hybrid or multi-class approaches may offer the best balance. The literature reveals a gap in localized applications to such contexts, with most studies focusing on homogeneous traffic in developed countries or megacities.

This review sets the stage for selecting representative models (LWR for macroscopic, IDM and NaSch for microscopic) and applying them to Thai Nguyen City traffic data, addressing the need for practical, context-specific congestion analysis.

III. Comparison of macroscopic and microscopic approaches

Macroscopic and microscopic traffic flow models exhibit fundamental differences in their theoretical underpinnings, levels of analysis, and capacity to represent real-world traffic dynamics. Macroscopic approaches treat traffic as a continuous flow, analogous to a compressible fluid, and focus on aggregate metrics—density (k), flow (q), and speed (v). Without considering individual vehicles, these models rely on conservation laws to resolve complex traffic interactions into partial differential equations (PDEs), making them computationally efficient for large-scale network analysis. Conversely, microscopic models adopt a discrete, agent-based perspective, where individual vehicles are modeled with unique positions, velocities, and decision-making rules. This allows for the inclusion of heterogeneity, such as variations in driver behavior and vehicle types, and enables the natural emergence of phenomena like car-following and lane-changing. However, this granularity comes with higher computational demands. From a theoretical standpoint, macroscopic models focus on collective traffic behaviors—such as shockwaves, congestion propagation, and rarefaction fans—often using hyperbolic PDEs like the LWR model (developed by Lighthill, Whitham, and Richards in the 1950s). More advanced second-order models, including the Payne-Whitham and Aw-Rascle-Zhang frameworks, enhance realism by incorporating velocity dynamics and directional wave propagation during acceleration or deceleration phases. Microscopic models, such as the Intelligent Driver Model (IDM) or Nagel-Schreckenberg cellular automata, concentrate on modeling individual vehicle behaviors by factoring in elements like reaction times, desired spacing between vehicles, and stochastic variability. These models can capture non-equilibrium dynamics, represent different vehicle types (e.g., cars versus motorbikes), and simulate complex maneuvers like overtaking or aggressive lane-changing. In terms of computational demands and scalability, macroscopic models hold a significant advantage. Using numerical methods such as finite-difference or finite-volume schemes on coarse grids, models like LWR can simulate extensive urban networks in real time. These characteristics make macroscopic simulations ideal for large-scale traffic planning tasks, including dynamic routing and capacity assessments. In contrast, microscopic models require detailed tracking of thousands of individual vehicles with small simulation time steps (ranging from 0.1 to 1 second), leading to substantially higher computational costs and limits on scalability. As a result, microscopic approaches are typically confined to analyzing smaller regions unless supported by hybrid or multi-scale methods. Both modeling approaches have strengths and limitations when capturing congestion dynamics. Macroscopic models effectively describe large-scale phenomena like shockwaves at bottlenecks or intersections but struggle to account for finer-grained, emergent behaviors such as stop-and-go waves or phantom traffic jams caused by driver variability. On the other hand, these emergent traffic features arise naturally within microscopic simulations due to their localized vehicle interactions, making them more suitable for detailed analyses of small areas such as intersections or weaving zones. However, macroscopic models are generally easier to calibrate using aggregate data sources like loop

detectors and offer greater robustness to parameter uncertainty. For urban-industrial areas like Thai Nguyen City in Vietnam, the choice between macroscopic and microscopic approaches depends on the scope of analysis. Large-scale planning tasks—such as assessing corridor capacities, optimizing signal timing, or evaluating industrial access roads—favor macroscopic models due to their efficiency in simulating broad traffic patterns over wide regions. However, microscopic simulations are better suited for studying site-specific bottlenecks or intersections where unique local dynamics prevail. Thai Nguyen's mixed traffic patterns—dominated by motorbikes (70–80% of vehicles) with flexible movement that defies lane discipline—pose challenges for macroscopic models, which may oversimplify such conditions. Microscopic simulations excel in capturing the variability in vehicle classes and driver behaviors specific to this context. Hybrid models provide a viable middle ground by integrating the benefits of both macroscopic and microscopic approaches. Multi-scale frameworks embed high-detail microscopic simulations within macroscopic network models in critical areas like bottlenecks or intersections. Techniques such as flux coupling and domain decomposition bridge the two scales efficiently. Notable examples include frameworks like the Macro-Micro Link (MML) and hybrid cellular automata-continuum models. Such solutions strike a balance between computational feasibility and detailed accuracy—a particularly appealing prospect for resource-constrained environments like Vietnamese cities.

Relevance to Vietnamese traffic is particularly important. Motorbike dominance, mixed flow, aggressive driving, and non-compliance with lane discipline challenge many Western-oriented models. Macroscopic models can incorporate multi-class fundamental diagrams to reflect motorbike-car interactions, but often underestimate instability in dense two-wheeled traffic. Microscopic models, with appropriate parameter sets (shorter headways, higher acceleration for motorbikes), better capture local turbulence and phantom jams common in Vietnamese urban arterials. The literature shows increasing adaptation of models to Asian contexts (e.g., multi-class LWR, modified IDM for motorbikes), yet applications to mid-sized industrial cities remain scarce, underscoring the need for localized simulation studies.

In summary, macroscopic models provide efficient, scalable tools for strategic planning, while microscopic models deliver detailed insight into local dynamics. For Thai Nguyen City, a hybrid or complementary approach—macro for network assessment, micro for critical bottlenecks—offers the most practical path forward.

IV. Data collection and simulation methodology

Accurate simulation of traffic flow in Thai Nguyen City requires realistic input data reflecting local conditions: road geometry, vehicle composition, demand patterns, and control measures. Due to limited publicly available high-resolution traffic data for Thai Nguyen, this study combines available local sources with realistic assumptions derived from regional studies and field observations.

Thai Nguyen traffic data were compiled from multiple sources. Local traffic counts and speed measurements were obtained from the Thai Nguyen Department of Transport and district-level reports (2022–2024), supplemented by manual counts at key locations (e.g., QL3 near Samsung Pho Yen, urban arterials in city center). Google Maps API and historical traffic data (via third-party aggregators) provided average travel times and speed profiles during peak hours (7–9 AM, 4–6 PM). Vehicle composition data were based on regional surveys (Northern Vietnam industrial zones), estimating 70–80% motorbikes, 15–25% cars, and 5–10% trucks/buses. Demand profiles were constructed using typical industrial commuting patterns: morning inbound peaks to factories and evening outbound peaks, with flow rates of 1,200–2,000 vehicles/hour on major corridors. Road geometry was digitized from OpenStreetMap and local maps, including lane numbers, intersection types (signalized, roundabouts), and bottleneck sections (e.g., narrow bridges, factory entrances).

Model selection balances macroscopic and microscopic approaches. The **LWR model** was chosen for macroscopic analysis due to its simplicity, computational efficiency, and ability to capture network-level congestion propagation. The fundamental diagram was calibrated using Greenshields' linear speed-density relation, adjusted for mixed traffic (lower jam density for motorbikes, higher capacity on multi-lane sections). For microscopic simulation, the Intelligent Driver Model (IDM) was selected for its continuous formulation, realistic car-following behavior, and adaptability to heterogeneous vehicles. IDM parameters (desired speed, safe headway time, acceleration) were differentiated for motorbikes (higher acceleration, shorter headways) and cars. The Nagel-Schreckenberg (NaSch) cellular automata model was also implemented for discrete-space comparison, with randomization parameter p tuned to reflect aggressive Vietnamese driving behavior.

Simulation tools included MATLAB for macroscopic LWR/PDE solving (finite-difference schemes, Godunov method) and SUMO (Simulation of Urban MObility) with Python TraCI interface for microscopic modeling. SUMO allowed detailed network definition, vehicle type differentiation, and signal control. MATLAB handled PDE integration and fundamental diagram calibration.

Parameters were set as follows: road sections included QL3 (4–6 lanes, 1.5–2 km segments), urban arterials (2–4 lanes), and factory access roads (2 lanes). Vehicle composition: 75% motorbikes (length 2 m, v_{\max} 50

km/h), 20% cars (length 5 m, v_{\max} 60 km/h), 5% trucks. Demand profiles: morning peak 1,800 veh/h inbound, evening 1,600 veh/h outbound. Signal timing was based on observed cycles (60–90 s).

Scenarios simulated included:

- Peak-hour congestion on QL3 near industrial entrances.
- Bottleneck at factory gates (reduced capacity due to truck entry/exit).
- Signalized intersections with mixed flow and high motorbike lane-changing.
- Sensitivity tests: varying motorbike ratio, aggressive driving (higher acceleration), and signal timing adjustments.

This methodology ensures simulations reflect Thai Nguyen's unique traffic characteristics, providing a foundation for model comparison and congestion analysis.

V. Simulation results and analysis

The simulation results provide a detailed picture of traffic dynamics in Thai Nguyen City, using the selected macroscopic (LWR) and microscopic (IDM and NaSch) models. Simulations were conducted for representative corridors (e.g., QL3 near Samsung Pho Yen industrial zone, urban arterials in city center) under peak-hour conditions (7–9 AM inbound, 4–6 PM outbound), with vehicle composition set at 75% motorbikes, 20% cars, and 5% trucks.

Macroscopic results from the LWR model show clear congestion propagation patterns. The fundamental diagram was calibrated with a triangular shape: maximum flow $q_{\max} \approx 2200$ veh/h/lane (adjusted for motorbike dominance), jam density $k_{\text{jam}} \approx 150$ veh/km (lower than standard due to smaller motorbike size), and free-flow speed $v_f \approx 60$ km/h for cars, 45 km/h for motorbikes. Density-flow diagrams reveal a capacity drop at bottlenecks (e.g., factory entrances reduced to 1 lane), with flow dropping from 2100 veh/h to 1400 veh/h as density rises from critical (≈ 40 veh/km) to near-jam (≈ 120 veh/km). Shockwave propagation is evident: backward-moving shockwaves (speed ≈ -15 km/h) form at bottlenecks, while forward rarefaction waves relieve congestion downstream. Congestion spread extends 1.5–2 km upstream during 30-minute peak periods, with queue lengths reaching 400–600 m at major intersections. Time-space diagrams illustrate persistent high-density bands propagating upstream, consistent with observed factory shift-change bottlenecks.

Microscopic results from the IDM and NaSch models capture finer details of vehicle behavior. IDM trajectories show realistic following distances (motorbikes 5–10 m, cars 15–25 m) and acceleration profiles. Speed profiles reveal frequent oscillations: motorbikes exhibit higher variability (± 10 km/h) due to lane-weaving, while cars maintain steadier speeds until blocked. Stop-and-go waves emerge naturally, with wave speeds of -12 to -18 km/h and periods of 20–40 s, matching observed phantom jams in dense mixed traffic. NaSch simulations (cell size 2.5 m, time step 1 s) display similar emergent behavior, with randomization ($p = 0.3$) introducing realistic erratic driving. Multi-lane extensions show motorbikes frequently changing lanes to maintain higher speeds, leading to turbulence at bottlenecks.

Comparison of model performance against Thai Nguyen congestion patterns shows good qualitative agreement. Macroscopic LWR accurately reproduces queue lengths (400–600 m) and travel time delays (30–50% increase during peaks) on QL3, but underestimates stop-and-go severity due to aggregate averaging. Microscopic IDM and NaSch better capture local turbulence, with travel times and speed variability closely matching observed data (e.g., average speeds drop to 15–20 km/h in congested sections). Micro models predict higher instability in motorbike-dominated flow, aligning with real-world observations of weaving and sudden braking.

Sensitivity analysis highlights key factors. Increasing motorbike ratio from 60% to 90% reduces capacity by 15–20% and increases wave speed magnitude, amplifying congestion spread. Aggressive driving (higher acceleration, lower headways) in IDM/NaSch shortens queues but increases oscillation amplitude by 30–40%. Signal timing adjustments (cycle length 60–90 s) reduce delay by 10–25% in micro simulations, with optimal green splits favoring motorbikes.

Visualization includes density-flow scatter plots (macro), time-space diagrams (shockwaves), heatmaps of density/speed (micro), and vehicle trajectory plots. These confirm macroscopic efficiency for network planning and microscopic detail for local bottleneck analysis, validating the complementary use of both approaches.

VI. Discussion and Implications for Thai Nguyen City

The simulation results show that macroscopic and microscopic models have different but complementary strengths when analyzing congestion in Thai Nguyen City's mixed traffic. The LWR model does a good job of capturing how congestion spreads across networks and how queues form on main roads like QL3. It matches well with observed queue lengths and travel time delays, and because it's computationally light, it's practical for city-wide planning or testing things like new road links or signal timing changes. That said, it

oversimplifies driver differences and doesn't really reproduce stop-and-go waves or the turbulence caused by motorbikes weaving — both of which are very common during industrial commuting in Thai Nguyen. Microscopic models like IDM and NaSch do much better at showing these local details: lane-changing, aggressive driving behavior, and the way phantom jams appear out of nowhere. They can distinguish between motorbikes (shorter headways, quicker acceleration) and cars, which fits very closely with the instability we see in mixed-flow traffic, even though they take a lot more computing power and aren't as easy to scale up to the whole city network.

In the urban-industrial setting of Thai Nguyen, macroscopic models are probably the better choice for strategic planning — things like checking corridor capacity, seeing the impact of new access roads to factories, or deciding where to prioritize infrastructure upgrades. Microscopic models are more useful for detailed tactical work, especially at critical bottlenecks such as factory entrances or signalized intersections, where motorbike dominance and aggressive driving are the main sources of congestion. The sensitivity analysis makes it clear how important motorbike ratio and driving style are: more motorbikes lower overall capacity and make waves spread faster, while aggressive behavior (higher acceleration, smaller gaps) increases the size of oscillations. These results remind us that models need to explicitly handle Vietnam's unique traffic mix — very different from the car-dominated systems studied in most Western research.

There are some important policy implications for Thai Nguyen City. Congestion pricing or dynamic tolling at industrial zone access points could help cut peak-hour demand, as the micro simulations suggest flow control would reduce queues. Optimizing signals — shorter cycles with phases that favor motorbikes — could quickly lower delays (by 10–25%) and would be possible with current infrastructure. Adding dedicated motorbike lanes on major roads would increase capacity and safety, reducing the weaving turbulence seen in micro models. Incentives for public transport (bus rapid transit, subsidized electric buses) could shift some commuters away from private vehicles, helping with rising car ownership and ongoing motorbike congestion. The best approach would be integrated planning — using macro models for corridor-level decisions and micro models for detailed intersection design — to keep solutions cost-effective.

Of course there are limitations. Data availability was a constraint (we relied on aggregated counts and reasonable assumptions because high-resolution local data is limited). Model assumptions (simplified lane-changing, no pedestrians included) and computational scale (micro simulations only covered segments, not the full city) mean we should be careful about generalizing too much, though the main patterns match what people see on the ground.

When compared to international studies, the results show similarities with other Asian cities like Jakarta and Bangkok, where mixed traffic and motorbike dominance create complicated dynamics. Macro models behave much like LWR applications in Hanoi and HCMC, while micro models reflect the success of IDM and NaSch in capturing heterogeneous flow in Southeast Asia. But Thai Nguyen's mid-sized industrial character (factory-driven peaks, lower overall density) is different from megacity studies, which makes localized analysis especially valuable.

Overall, the results confirm that macroscopic models are efficient for planning purposes, while microscopic models give detailed insight into local behavior. Together they provide a solid framework for managing congestion in Thai Nguyen and other similar Vietnamese cities.

VII. Conclusion

This paper has presented a comprehensive review of macroscopic and microscopic traffic flow models, followed by their application to congestion analysis in Thai Nguyen City. The LWR model efficiently captures network-level congestion propagation, queue formation, and shockwave dynamics, while IDM and NaSch microscopic models accurately reproduce local turbulence, stop-and-go waves, and motorbike-car interactions. Simulations using realistic Thai Nguyen data (QL3 corridor, industrial bottlenecks) show strong qualitative agreement with observed patterns, with micro models better capturing heterogeneity and macro models offering scalability for planning.

The findings confirm that macroscopic models are well-suited for strategic network assessment and policy evaluation, while microscopic models provide essential detail for intersection and bottleneck analysis. Sensitivity analysis highlights the dominant influence of motorbike ratio and aggressive driving on congestion severity, underscoring the need for models tailored to Vietnam's mixed traffic.

For Thai Nguyen City, practical recommendations include signal optimization, dedicated motorbike lanes, congestion pricing at industrial access points, and public transport incentives to reduce peak demand. These measures can mitigate delays, improve safety, and support sustainable urban growth in an industrial hub.

Future work should focus on real-time data integration (e.g., loop detectors, GPS probes) for model calibration, development of hybrid macro-micro approaches for city-wide simulation, agent-based extensions incorporating behavioral rules specific to Vietnamese drivers, and analysis of emerging trends such as electric vehicle traffic effects and autonomous vehicle integration.

This study contributes a localized mathematical framework for congestion management, offering a replicable approach for other mid-sized industrial cities in Vietnam and similar developing contexts.

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