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THE RELATIONSHIP BETWEEN TRAFFIC FLOW AND INTERSECTION TYPES: A CASE STUDY OF HO CHI MINH CITY

Phu Tran, Duy-Thoi Do, Vu-Tu Tran

Faculty of Civil Engineering, Ho Chi Minh City University of Technology and Engineering, Ho Chi Minh City, Vietnam
Corresponding Author: tutv@hcmute.edu.vn

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Abstract: This study examines the relationship between traffic flow characteristics and the selection of intersection types under mixed-traffic conditions in Vietnam. Existing frameworks, such as the Lobanov (1970) diagram, were originally developed for homogeneous automobile flows and thus fail to reflect the complex interactions of motorcycle-dominated streams. To bridge this gap, a context-sensitive Intersection Type Selection Chart was developed by integrating empirical data processing, Passenger Car Unit (PCU) conversion, and microscopic simulation in PTV VISSIM. Field data from the Hoang Dieu 2–To Vinh Dien intersection in Thu Duc City were used to simulate three intersection types: non-signalized, signalized, and grade-separated intersections across multiple flow combinations. Average control delays were analyzed and classified on a two-dimensional (X, Y) plane to delineate operational boundaries among the three regimes. The resulting chart reveals a clear hierarchical transition: non-signalized intersections perform best at low volumes ($X < 1500$ PCU/h, $Y < 800$ PCU/h); signalized intersections are suitable for medium volumes ($1500 \le X \le 2200$ PCU/h); and grade-separated designs are necessary when both flows exceed 2200 PCU/h. Compared with Lobanov's original model, the thresholds shift to lower ranges due to the reduced effective capacity and lane discipline of mixed traffic. The developed chart provides a practical, data-driven tool for planners and engineers to guide intersection type selection in Vietnam's rapidly urbanizing cities.

Keywords: Mixed traffic, Intersection type selection, Control delay, PTV VISSIM, Lobanov model.

1. Introduction

Vietnam is among the most rapidly motorizing countries in Southeast Asia, driven by accelerated urbanization, population growth, and economic transformation. Over the past two decades, the number of private vehicles, particularly motorcycles, has grown exponentially. Vietnam has one of the highest motorcycle ownership rates in the world. Motorcycles have historically dominated urban traffic in Vietnam, accounting for more than 80% of transportation flow in major cities such as Hanoi and Ho Chi Minh City (Minh et al., 2005). Recent urban development trends have also shown a gradual increase in private car ownership, particularly in metropolitan areas. According to recent statistics from national and municipal transport agencies, the absolute number and modal share of private cars have risen steadily over the past decade. Nevertheless, motorcycles continue to dominate urban traffic streams in terms of numerical share and operational influence, especially at intersections, where mixed vehicle interactions, lane-sharing behavior, and queue discharge characteristics remain largely motorcycle-driven. Even with increasing car ownership, motorcycles still represent the primary determinant of intersection performance under typical peak-hour conditions. Therefore, this study adopts a mixed-traffic perspective that explicitly accounts for both motorcycle dominance and the growing presence of private cars, ensuring that the proposed intersection selection framework remains applicable under current and transitional urban traffic conditions in Vietnam.

Intersections represent critical nodes in urban transport systems, where conflicting traffic movements, high volumes, and heterogeneous vehicle behavior converge. In Vietnam, frequent congestion, safety hazards, and operational inefficiencies at intersections have become common problems, especially during peak hours. The capacity and control type of intersections, whether non-signalized, signalized, or grade-separated, strongly determine the efficiency and safety of the overall traffic network. Therefore, selecting the appropriate intersection type is a fundamental aspect of sustainable and

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resilient urban traffic planning. However, most existing international design standards and selection models, such as the intersection selection diagram proposed by E. M. Lobanov, were developed for automobile-dominated traffic in developed countries (Lobanov, 1970). These models often fail to represent Vietnam's unique traffic composition, where motorcycles, bicycles, and informal vehicles coexist in flexible and lane-free traffic streams. As a result, the direct adoption of such frameworks may lead to suboptimal intersection design and limited operational performance under local conditions.

To address this gap, it is essential to develop a locally adapted decision-support framework for intersection type selection that reflects the empirical characteristics of Vietnam's mixed traffic. This study aims to establish such a framework through an integrated approach combining field observation, data analysis, and microscopic traffic simulation using PTV VISSIM Version 2021 (PTV Group, 2022a). The research analyzes the operational performance of three major intersection types, non-signalized, signalized, and grade-separated, under various traffic flow scenarios, using a case study of the Hoang Dieu 2–To Vinh Dien intersection in Thu Duc City, Ho Chi Minh City. By calibrating simulation models with real-world data and comparing average control delays across multiple volume combinations, the study identifies threshold values that define optimal operating conditions for each intersection type. The resulting intersection selection chart provides a practical decision-making tool for transport planners and engineers. It supports data-driven design choices aimed at improving intersection efficiency, reducing congestion, and enhancing urban mobility in Vietnam's rapidly urbanizing cities.

2. Literature Review

2.1. Mixed Traffic Characteristics in Developing Countries

In developing countries, particularly across Asia and Africa, traffic systems are typically heterogeneous, where multiple vehicle types (motorcycles, passenger cars, bicycles, minibuses, light trucks, etc.) share the same road space without strict lane discipline. Such conditions make traditional homogeneous traffic models inadequate for describing flow characteristics and operational performance (Verma, 2016).

Tran and Shimizu examined the group behavior of motorcycle streams during left-turn and through movements, revealing that in Vietnamese urban settings motorcycles tend to form flexible clusters and opportunistically occupy available gaps, leading to complex merging and weaving conflicts (V. T. P. Tran & Shimizu, 2011). In a notable study conducted in Ho Chi Minh City, Tuan and Man analyzed mixed-traffic saturation flows at signalized intersections and developed adjustment factors to account for motorcycle dominance, roadway width, and green-time allocation (Tuan & Man, 2015). Similarly, Huynh et al. observed that motorcycles accounted for up to 92% of total traffic volume during peak periods at intersections in Ho Chi Minh City, and that correlations between left-turn and through movements remained relatively weak under unsaturated conditions (Huynh et al., 2013).

In addition, recent work by Do and Tran has highlighted both the strengths and limitations of applying agent-based modelling approaches to traffic and transportation systems, particularly in the context of intersection operations. Their findings indicate that multi-agent frameworks are well suited to capturing heterogeneous vehicle interactions, adaptive behaviour, and localized decision-making processes, but also require careful calibration to balance model complexity and computational efficiency (Do & Tran, 2025).

From these studies, two key insights can be drawn. First, classical car-following models are difficult to apply directly to heterogeneous traffic conditions. Second, it is necessary to adopt modified or alternative modelling approaches, such as gap-acceptance models, social-force models, or hybrid frameworks, to more accurately represent traffic flow and the complex interactions among different vehicle types.

2.2. Control Strategies and Intersection Types

Efficient traffic management at intersections depends not only on geometric design but also on the choice of control strategy that governs vehicle interactions and right-of-way allocation. In mixed-traffic environments, the selection of an appropriate intersection type, namely non-signalized, signalized, or grade-separated intersections, directly determines overall capacity, safety, and operational stability. Each configuration exhibits distinct advantages and limitations under varying traffic volumes and traffic compositions. Therefore, a systematic review of control principles and empirical findings related to these intersection types is essential to establish a foundation for developing a context-sensitive selection framework suitable for Vietnam's urban road networks.

Signalized Intersections. Signalized intersections remain the most widely adopted solution for managing traffic conflicts in urban environments. Qadri et al. (2020) summarized recent advances in signal control, ranging from heuristic and meta-heuristic algorithms to deep-learning-based systems, aimed at enhancing traffic efficiency and minimizing congestion. More recent work by Li et al. (2024) integrated deep reinforcement learning to optimize signal timing under mixed-traffic conditions, demonstrating its potential for real-time adaptive control in developing cities. Additionally, social-force modelling has been applied to simulate vehicle interactions at signalized intersections with heterogeneous traffic compositions, accounting for lane encroachment, opportunistic behavior, and variable headways (Huynh et al., 2013).

Grade-Separated Intersections. Grade-separated intersections, such as overpasses and underpasses, are widely recognized for their superior operational capacity because they physically eliminate crossing conflicts. However, their implementation must consider land-use interactions, accessibility, and high construction costs. Shokry et al. (2017)

compared at-grade and grade-separated intersections in terms of land-use efficiency and concluded that although grade separation enhances mobility, it may reduce pedestrian connectivity and adjacent land accessibility. He et al. (2016) proposed partially grade-separated signalized intersections to reduce crossing conflicts while maintaining operational flexibility through signal control. The Federal Highway Administration (FHWA) also published comparative guidelines on Alternative Intersections/Interchanges (AIIs), identifying hybrid designs such as Continuous Flow Intersections (CFIs) and Diverging Diamond Interchanges (DDIs) as cost-effective alternatives between at-grade and fully grade-separated systems (Hughes et al., 2010). Cunningham et al. (2022) further analyzed unconventional grade-separated intersections and emphasized the importance of geometric continuity, signage, and merging design for ensuring safety and user comprehension.

Comparative Performance of Intersection Types. Several studies have compared the operational performance of non-signalized, signalized, and grade-separated intersections to identify optimal operating conditions. Shokry et al. (2017) found that although grade-separated intersections generally outperform other intersection types in terms of capacity and delay reduction, they require careful cost–benefit evaluation and contextual adaptation. In addition, recent studies have introduced Unconventional Arterial Intersection Designs (UAIDs), such as CFIs and Restricted Crossing U-Turns (RCUTs), as transitional alternatives between at-grade and grade-separated designs (Hughes et al., 2010). Kalasova et al. (2024) evaluated traffic optimization strategies among various intersection types and highlighted the role of simulation tools such as PTV VISSIM in assessing operational efficiency under specific traffic-flow conditions. Beyond intersection-focused analyses, microscopic simulation tools such as PTV VISSIM have also been shown to effectively capture the performance implications of traffic control strategies and geometric constraints under complex traffic conditions (V.-T. Tran & Do, 2025).

2.3. Volume Thresholds and Evaluation Criteria

Determining the appropriate intersection type fundamentally depends on identifying the critical traffic-volume thresholds at which each control strategy, namely non-signalized, signalized, or grade-separated intersections, performs most effectively. Empirical studies have attempted to quantify these thresholds to support practical decision-making. These thresholds are typically expressed in passenger car units per hour (PCU/h) or combined approach volumes and reflect the operational balance between traffic demand and intersection capacity. According to the Highway Capacity Manual (HCM), capacity and Level of Service (LOS) analyses provide the theoretical foundation for assessing such thresholds under homogeneous traffic conditions (Transportation Research Board, 2000a). However, in mixed-traffic environments such as Vietnam, the direct application of these standards requires substantial recalibration because motorcycles and informal vehicles influence lane utilization, queue formation, and saturation-flow characteristics differently (Tuan & Man, 2015).

Key performance indicators (KPIs) commonly used to evaluate intersection performance include average control delay, throughput, queue length, conflict frequency, and safety-related measures. Among these indicators, average control delay remains the most widely adopted performance metric because it directly reflects the trade-off between operational efficiency and user comfort (Li et al., 2024; Qadri et al., 2020). Nevertheless, contemporary decision-support frameworks increasingly incorporate additional criteria, such as accident frequency, emission levels, construction costs, and land-use compatibility, to capture both operational and socio-environmental dimensions of performance (Hughes et al., 2010; Shokry et al., 2017).

Recent simulation-based studies have sought to identify quantitative transition points between different intersection-control strategies. Kalasova et al. (2024) demonstrated that under relatively low traffic volumes, non-signalized intersections may outperform signalized intersections in terms of delay and energy consumption. However, once traffic demand exceeds a critical threshold, delays increase nonlinearly and signal control becomes necessary to maintain operational stability. At even higher traffic volumes, grade-separated designs often emerge as the only feasible alternative because they provide uninterrupted traffic flow despite requiring substantially greater capital investment. Similar findings reported by He et al. (2016) and Hajbabaie et al. (2024) indicate that these transitions can be represented as nonlinear response curves, in which relatively small increases in traffic demand may trigger substantial deterioration in operational performance.

In this context, identifying context-specific threshold values, for example, the transition from non-signalized to signalized control when total approach volume exceeds approximately 1,500 PCU/h, or from at-grade to grade-separated configurations when traffic volumes exceed 4,000–5,000 PCU/h, provides valuable guidance for transportation planners and engineers. Once validated under Vietnam's mixed-traffic conditions through empirical observation and microscopic simulation using tools such as PTV VISSIM, these thresholds can form the quantitative foundation of a data-driven intersection-selection framework. Such a framework would enable planners to balance efficiency, safety, and cost considerations while ensuring the long-term adaptability of urban transportation networks to future traffic growth.

2.4. Research Gaps

Despite considerable global research on intersection performance and control optimization, several critical gaps remain in understanding how different intersection types operate under mixed-traffic conditions such as those found in Vietnam and other Southeast Asian countries.

First, most capacity and delay models, including those presented in the Highway Capacity Manual (HCM), are fundamentally based on homogeneous and automobile-dominated traffic environments (Transportation Research Board, 2000a). When directly applied to motorcycle-prevalent networks, these models fail to adequately capture lane-sharing behavior, lateral movements, and the stochastic interactions among motorcycles, passenger cars, and informal vehicles. Although local studies have attempted to adjust Passenger Car Unit (PCU) conversion factors for Vietnamese conditions (Tuan & Man, 2015), a comprehensive recalibration of the underlying analytical framework remains lacking.

Second, existing intersection-selection guidelines rarely incorporate empirical threshold values that define transitions between intersection types under mixed-traffic conditions. Although these frameworks distinguish among broad functional categories, namely non-signalized, signalized, and grade-separated intersections, they do not quantify the operational limits at which one design begins to outperform another in terms of delay, queue length, or safety performance. Consequently, their direct applicability to rapidly motorizing cities remains limited.

Third, while recent simulation-based studies have introduced advanced analytical tools, including PTV VISSIM, MATLAB SimEvents, and deep reinforcement learning, most investigations have been conducted under controlled or idealized conditions (He et al., 2016; Kalasova et al., 2024; Li et al., 2024). There remains a shortage of calibrated microscopic simulation models based on real-world traffic data from Vietnam, where traffic composition, driver behavior, and signal coordination differ substantially from those observed in developed countries.

Fourth, the existing literature continues to treat intersection performance primarily as an engineering optimization problem, emphasizing delay reduction and throughput maximization while paying relatively limited attention to socio-spatial and environmental considerations such as pedestrian accessibility, air-quality impacts, and energy consumption. Incorporating these dimensions would enable a more comprehensive evaluation framework aligned with the principles of sustainable urban mobility.

Finally, relatively few studies explicitly address dynamic planning applications in which intersection-type selection is linked to projected traffic growth, network evolution, and adaptive management strategies. Developing a data-driven decision-support tool capable of visualizing transition thresholds over time, for example through trajectories represented in the N_c–N_0 flow space, would address an important methodological gap and support proactive rather than reactive traffic management.

Addressing these research gaps requires the integration of empirical field observations, calibrated microscopic simulation, and context-sensitive modelling approaches to establish a reliable intersection-selection framework tailored to mixed-traffic conditions in Vietnamese cities. Such a framework would not only improve technical decision-making but also contribute to broader objectives of sustainable, safe, and resilient urban mobility.

3. Methodology

The methodological framework of this study is designed with the ultimate objective of developing an Intersection Selection Chart for mixed-traffic conditions in Vietnam, where motorcycles constitute the dominant share of total traffic flow. The proposed chart conceptually builds upon the classical model developed by Lobanov (1970), which identifies appropriate intersection types based on the relationship between major-road traffic volume (N_c) and minor-road traffic volume (N_o) under homogeneous, automobile-dominated traffic conditions (Figure 1). However, the original Lobanov diagram was established in the context of developed countries, where vehicle movements generally follow strict lane discipline and passenger cars dominate traffic streams. Such assumptions are inconsistent with Vietnam's mixed-traffic environment, which is characterized by a high proportion of motorcycles, bicycles, and informal vehicles sharing limited roadway space. Consequently, the direct application of Lobanov's model may result in substantial inaccuracies when evaluating intersection performance and determining operational thresholds under Vietnamese traffic conditions.

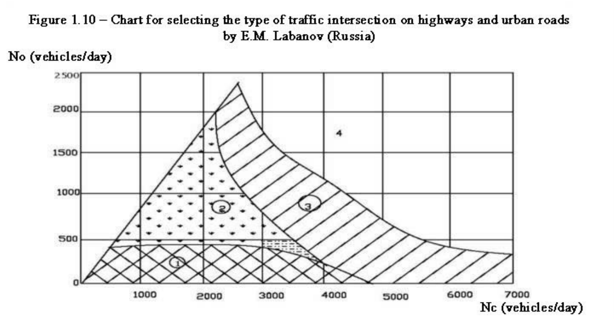

Figure 1: LChart for selecting the type of traffic intersection on highways and urban road. Source: (Lobanov et al.,1970)

To address these limitations, the present study adopts, calibrates, and extends the theoretical framework proposed by Lobanov (1970) through the integration of empirical observations and microscopic traffic simulation. By combining field traffic surveys, traffic-volume standardization using Passenger Car Units (PCUs), and simulation modelling in PTV VISSIM, the study aims to develop a context-sensitive Intersection Selection Chart capable of accurately defining the operational boundaries of three major intersection types: non-signalized, signalized, and grade-separated intersections.

The resulting chart is intended to provide quantitative threshold values that identify the most appropriate operating conditions for each intersection type under Vietnam's mixed-traffic environment. In doing so, it offers a scientifically grounded and practically applicable decision-support tool for transportation planners and traffic engineers, enabling the planning, design, management, and upgrading of intersections based on data-driven evaluation rather than solely on empirical experience.

The overall methodological framework consists of four primary phases: (1) field traffic data collection; (2) data processing and simulation-input preparation; (3) microscopic simulation of the three intersection types using PTV VISSIM; and (4) output analysis and development of the proposed Intersection Selection Chart (Table 1).

Table 1: Summary of the calculation and simulation framework

Step	Description	Output
1	Field traffic survey (2025)	Directional volumes (veh/h)
2	PCU conversion (TCVN 13592:2022)	Standardized flows (PCU/h)
3	Scenario definition	(N_c, N_0) combinations
4	VISSIM simulation	Control delay (s/veh)
5	Performance comparison	Optimal intersection type
6	Boundary extraction	Intersection Selection Chart

3.1. Traffic Data Collection

Field data were collected at the Hoang Dieu 2-To Vinh Dien intersection in Thu Duc City, Ho Chi Minh City (Figure 2), which is representative of Vietnam's urban mixed-traffic environment characterized by a high proportion of motorcycles, heterogeneous vehicle interactions, and frequent directional conflicts.

Although empirical datasets collected in 2010 and 2017 are referenced in this study, they are used exclusively as benchmark sources to contextualize mixed-traffic characteristics reported in previous research, including vehicle-composition patterns, Passenger Car Unit (PCU) conversion factors, and general traffic-behaviour characteristics. These historical datasets were not used as direct inputs for simulation modelling or performance evaluation.

The primary dataset employed for model calibration and simulation analysis was obtained through field observations conducted in April 2025 at the study intersection. The dataset includes traffic volumes, directional flow distributions, signal-timing parameters, and operational performance measures under contemporary mixed-traffic conditions in Ho Chi Minh City. By utilizing recent field observations for both simulation inputs and model validation, the proposed Intersection Selection Chart reflects current traffic characteristics and operational conditions rather than historical traffic states.

Figure 2: Location of the Hoang Dieu 2-To Vinh Dien intersection. Source: (Google map 2025)

The survey was conducted during the peak hour (10:00–11:00, April 1, 2025) through direct manual counts and video recording. The collected datasets included:

Traffic composition: motorcycles, passenger cars, buses, light and heavy trucks, and bicycles.

Movement patterns: 12 turning and through directions (Figure 3). The traffic volumes of different vehicle types by movement directions are illustrated in Figure 4.

Geometric characteristics: number of lanes, lane width (3.5 m), approach lengths, and intersection angles.

Signal operation data: total cycle length (60 s), green time (30 s per phase), and signal phasing plan.

Total traffic flows were aggregated into 15-minute intervals, the peak 15-minute flow(V15), hourly total flow (V) and The Peak Hour Factor (PHF) was calculated as (1) and are shown in Table 2.

$$PHF = \frac{V}{4 \times V_{15}} \tag{1}$$

3.2. Data Processing and Input Preparation

The raw traffic data collected from field observations were processed and standardized to form compatible input datasets for simulation. This process involves two main procedures: (1) Conversion of observed volumes to Passenger Car Units (PCU) to normalize heterogeneous traffic, and (2) Aggregation of geometric, operational, and control parameters required for model input. To facilitate transparency and reproducibility, the key input parameters used in this study are summarized in Table 3, including traffic survey conditions, geometric characteristics, signal control settings, and PCU conversion references. Presenting these inputs in tabular form allows

Table 2: Peak hour calculation and PHF

Time	**10h–10h15**	**10h15–10h30**	**10h30–10h45**	**10h45–11h00**
Total flow	1181	1048	1112	1355
The peak 15-minute flow		1355		
Hourly total flow		4696		
Peak Hour Factor (PHF)		0.87		

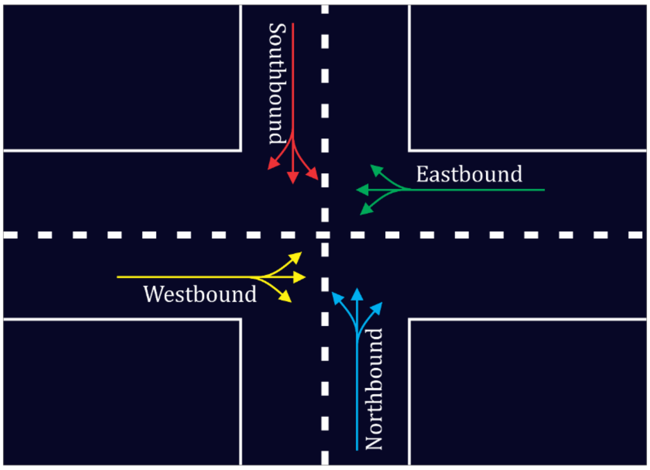

Figure 3: Illustration of Vehicle Movement Directions at the Intersection

readers to quickly identify the assumptions and boundary conditions adopted in the simulation model.

3.2.1. Conversion to Passenger Car Units (PCU)

In Vietnam's mixed traffic conditions, motorcycles typically account for 80–90% of the traffic stream. Consequently, direct comparison based on raw vehicle counts may not accurately reflect the operational characteristics of heterogeneous traffic. To standardize different vehicle classes, the observed traffic volume V (veh/h) was converted into an equivalent passenger car unit flow (PCU/h) according to the following equation:

$$Q_{\mathrm{PCU}} = \sum_{i=1}^{n} q_i \times f_i \tag{2}$$

where Q_{PCU} is the equivalent traffic flow expressed in passenger car units per hour (PCU/h); q_i is the hourly traffic volume of vehicle type i (veh/h); f_i is the corresponding PCU conversion factor for vehicle type i; and n is the total number of vehicle classes in the observed traffic stream. The conversion factors were adopted from TCVN 13592:2022, Passenger Car Unit Conversion for Mixed Urban Traffic, which considers vehicle dimensions, operational characteristics, and the relative interference effects among different vehicle types (Ministry of Science and Technology of Vietnam, 2022). Table 4 presents the PCU coefficients used in this study.

It should be noted that although the reference PCU factors in Table 4 are reported at a nominal speed of 60 km/h, as specified in TCVN 13592:2022, the present study does not directly apply a speed-based equivalency transformation. This is because the analysis focuses on urban intersection conditions, where operating speeds are governed by signal control, geometric characteristics, and traffic interactions rather than free-flow speed limits. In inner-city environments such as Ho Chi Minh City, average approach speeds typically range between 40–50 km/h, and vehicle interactions are dominated by start–stop behavior, queue discharge, and gap acceptance at intersections. Under these conditions, PCU values primarily reflect relative space occupancy and interaction effects among vehicle types rather than speed alone. Therefore, the adopted PCU factors are considered representative for comparative performance analysis across intersection types, provided that the same conversion scheme is consistently applied to all simulated scenarios.

Moreover, the proposed Intersection Type Selection Chart is derived from relative delay-based performance comparisons under identical traffic demand conditions. As such, the chart is insensitive to absolute speed assumptions, and no additional speed-based PCU equivalency transformation is required.

This conversion transforms the mixed vehicle stream into a uniform measure that can be directly used for capacity analysis and simulation calibration. The PCU-based approach aligns with the equivalency principle described in the Highway Capacity Manual (HCM 2000), ensuring consistency in the determination of Level of Service (LOS) and delay across different vehicle classes (Transportation Research Board, 2000b). Although the converted traffic flows expressed in PCU/h for each approach were computed during data processing, only the aggregated veh/h values are presented in this paper for conciseness. The PCU-based flows were, however, used as the direct input for simulation calibration in VISSIM.

3.2.2. Calculation of Directional Flows and Approach Flow

For each approach, total traffic volumes were disaggregated by movement type (left-turn, through, and right-turn). The directional distribution factor D was defined as:

$$D = \frac{Q_m}{Q_t} \tag{3}$$

where Q_m is the combined traffic flow of the major-road approaches (veh/h), and Q_t is the total entering traffic flow at the intersection (veh/h). This parameter allows proper scaling of major-road and minor-road traffic demands during scenario

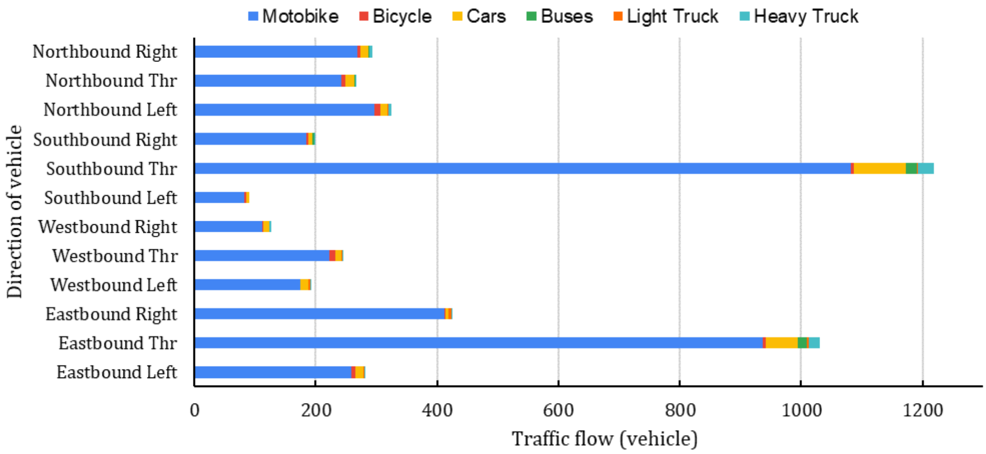

Figure 4: Directional Traffic Flow Distribution by Vehicle Type at the Intersection

Table 3: Summary of input data used in the simulation

Category	Parameter	Value / Source
Traffic data	Survey time	10:00–11:00, April 1, 2025
Traffic composition	Motorcycles, cars, buses, trucks	Field survey
Signal control	Cycle length	60 s
Signal control	Effective green	30 s
Geometry	Lane width	3.5 m
PCU factors	Motorcycle / Car / Truck	TCVN 13592:2022

generation. The total traffic volumes for each approach direction are summarized in Table 5.

Based on the observed traffic volumes, the Eastbound and Southbound approaches exhibit significantly higher flow rates compared to the other directions. Therefore, rather than defining a continuous major street, such as East–West, these two heaviest intersecting approaches were grouped and identified as the "dominant conflicting flows" for subsequent analysis. This selection ensures that the simulation model accurately reflects the heaviest traffic load that dictates the intersection's signal timing and delay.

The directional distribution factor (D) was calculated explicitly as follows:

$$D = \frac{V_{\text{dominant}}}{V_{\text{total}}} = \frac{1738 + 1507}{4696} = \frac{3245}{4696} \approx 0.69 \quad (4)$$

This indicates that roughly 69% of the total intersection volume is driven by these two dominant approaches, which together constitute the dominant conflicting flow (N_n) used in all subsequent simulation scenarios.

The PCU-based directional and approach volumes obtained from this process were subsequently used as the input data for the VISSIM simulation model. Employing PCU/h rather than veh/h allows the model to more accurately capture the effects of mixed traffic, particularly the dominance of motorcycles in the observed stream. This normalization ensures that variations in vehicle composition among the three simulation scenarios, namely low, medium, and high volume conditions, are consistently represented in terms of equivalent capacity and space occupancy. As a result, the simulation outcomes, such as delay, queue length, and Level of Service, are more directly comparable across all modeled conditions.

3.2.3. Scenario Design and Volume Matrix

Based on the PCU-converted and directionally distributed traffic data, ten representative combinations of major-road flow (N_c) and minor-road flow (N_0) were defined to represent a wide range of intersection operating conditions, ranging from under-saturated to over-saturated traffic states. The scenario matrix adopted a two-dimensional design, varying N_c from 400 to 5000 PCU/h and N_0 from 300 to 2400 PCU/h. Incremental steps were selected to provide sufficient resolution for interpolating the final Intersection Selection Chart. The complete scenario matrix is presented in Table 6.

Each scenario corresponds to a distinct operating point (N_c, N_0), which serves as an input pair for the simulation experiments conducted in VISSIM. The combined Eastbound and Southbound flows, identified as the dominant conflicting flows (Section 3.2.2), were used to represent N_c, whereas the combined Westbound and Northbound flows were used to represent N_0. This configuration maintains consistency with the observed traffic distribution factor ($D = 0.69$) and allows the simulated intersection to reflect realistic flow interactions under varying demand levels.

Table 4: The PCU coefficients

Vehicle Type	Motorcycle	Bicycle	Cars	Buses	Light Truck	Heavy Truck
PCU Factor (at 60 km/h)	0.5	0.5	1.0	2.0	2.5	3.0

Table 5: The total traffic volumes for each approach direction

Direction	Eastbound	Westbound	Southbound	Northbound
Total Volume (veh/h)	1738	565	1507	886

The ten scenarios collectively form the data foundation for constructing the Intersection Selection Chart, analogous to the two-axis framework proposed by Lobanov (Lobanov, 1970). By systematically varying both N_c and N_0, the framework enables a comprehensive evaluation of intersection performance under different traffic demand combinations and facilitates the identification of operational boundaries between alternative intersection control types.

The traffic volumes and corresponding field-observed delays were directly used as inputs for model calibration and validation. No additional behavioral parameters, such as speed distributions or acceleration profiles, were specified because these effects were implicitly reflected in the observed delays and the default driver behavior settings implemented in PTV VISSIM. This approach ensures consistency between empirical observations and simulation conditions while focusing the analysis on flow–delay relationships rather than variations in driver behavior.

3.2.4. Delay Estimation and Application in Simulation

In accordance with the Highway Capacity Manual (HCM 2000) (Transportation Research Board, 2000b), control delay represents the additional travel time experienced by a vehicle due to deceleration, queue formation, stopped delay, and subsequent acceleration at an intersection. It serves as the primary performance indicator for determining the Level of Service (LOS) and evaluating intersection operations. The average control delay per vehicle (d) can be expressed as:

$$d = \frac{3600\left(\frac{V}{C} - 1\right)}{v} + t_q \quad (5)$$

where V/C is the volume-to-capacity ratio, v is the traffic volume (veh/h), and t_q is the average queue delay component obtained from field observations or model output.

In this study, the average control delay (s/veh) for each approach and lane group was derived from field observations (see Table 7). These empirical delay values were used both for calibration of the VISSIM simulation model and for validation of the simulated results across the ten traffic volume scenarios. This procedure ensures that the simulated flow-delay relationships remain consistent with observed intersection performance under mixed-traffic conditions.

In this study, the average control delay (s/veh) for each approach and lane group was derived from field observations (see Table 7). These empirical delay values were used both for calibration of the VISSIM simulation and for validating the consistency of the simulated results across ten volume scenarios. This ensures that the simulated flow-delay relationships align with real-world intersection performance under mixed traffic conditions.

3.3. *Simulation in PTV VISSIM*

Microscopic simulation was performed using PTV VISSIM 2022, which provides a flexible platform for analyzing complex and lane-free traffic conditions such as those observed in Vietnam. The simulation aimed to evaluate the operational performance of three intersection types—non-signalized, signalized, and grade-separated—across ten defined traffic volume scenarios (Section 3.2.4). The geometric model of the Hoang Dieu 2 – To Vinh Dien intersection, as implemented in VISSIM, is illustrated in Figure 5.

Model Configuration The geometric layout of the Hoang Dieu 2–To Vinh Dien intersection was replicated in VISSIM based on detailed field measurements, including lane widths, approach lengths, intersection angles, and turning radii. Traffic inputs were defined using the converted approach volumes (PCU/h) and the directional flow distribution factor (D) derived from field data. The observed delay values were used for model calibration, ensuring that the simulated travel times and queue lengths reflected the observed intersection performance. The simulation adopted VISSIM's default Wiedemann 99 car-following model and lane-change logic without parameter modification, as no empirical driving-behavior data were available for this site. This approach is consistent with prior Vietnamese studies that used standard VISSIM behavioral settings for preliminary model validation (D. Q. Tran et al., 2021). Future research may extend this model by locally calibrating Wiedemann parameters and desired speed distributions once sufficient trajectory data become available.

Simulation Design The simulation experiments were designed to evaluate the operational performance of the intersection under varying traffic demand levels and control types. Each of the ten traffic scenarios, representing distinct combinations of major-road flow (N_c) and minor-road flow (N_0), ranging from 400–5000 PCU/h and 300–2400 PCU/h, respectively, was simulated for three intersection configurations.

The non-signalized intersection represents yielding-based operation without traffic signals under low-volume and

Table 6: Traffic volume scenarios used in simulation

Scenario	N_c (PCU/h)	N_0 (PCU/h)	Traffic condition
S1	400	300	Low
S2	911	533	Low–Medium
S3	1422	767	Medium
S4	1933	1000	Medium
S5	2444	1233	Medium–High
S6	2956	1467	Medium–High
S7	3467	1700	High
S8	3978	1933	High
S9	4489	2167	Very High
S10	5000	2400	Oversaturated

Table 7: The average control delay for each approach direction

Direction	Eastbound	Westbound	Southbound	Northbound
Average control delay (s/veh)	14.265	8.395	25.219	0.208

unsaturated conditions. It should be noted that simulating a non-signalized condition is not intended to reflect the current heavy-traffic condition of the studied intersection. Instead, the real-world intersection serves as a geometric baseline. The non-signalized configuration is applied to hypothetically low-volume scenarios, such as Scenario S1 with 400 PCU/h, to identify the theoretical performance boundary where signalization becomes operationally required.

The signalized intersection represents fixed-time control using the observed 60-second cycle and 30-second effective green phase on the major approach. The grade-separated intersection represents complete physical separation of conflicting movements, modeled using two vertical levels with dedicated ramps for through and turning movements.

Each scenario was simulated for 3600 seconds of effective runtime after a 300-second warm-up period to eliminate transient effects. Following PTV VISSIM 2022 and HCM 2000 recommendations (PTV Group, 2022b; Transportation Research Board, 2000b), each configuration was replicated three times with different random seeds to account for stochastic variation. The mean values of key performance indicators, including delay, queue length, and Level of Service (LOS), were extracted for subsequent analysis.

Figure 5: Geometric layout of the Hoang Dieu 2 – To Vinh Dien intersection modeled in PTV VISSIM

Model Calibration and Validation Model calibration was performed by comparing the simulated and observed average control delays for each intersection approach. The calibration objective was to minimize the deviation between simulated results from PTV VISSIM and observed field data. The accuracy of calibration was evaluated using the Mean Absolute Percentage Error (MAPE), calculated as:

$$\text{MAPE} = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{d_{s,i} - d_{o,i}}{d_{o,i}} \right| \tag{6}$$

where $d_{s,i}$ is the simulated average control delay for approach i (s/veh), $d_{o,i}$ is the observed average control delay for approach i (s/veh), and n is the number of observed approaches.

Calibration was considered satisfactory when MAPE < 10%, following the acceptable threshold recommended by the Highway Capacity Manual and similar studies on mixed traffic flow calibration (Transportation Research Board, 2000b). Once the calibrated parameters achieved this accuracy level, the model was validated by running additional simulations under the same traffic volume conditions. The validation aimed to verify the stability and reproducibility of the delay–flow relationships across intersection types.

Output Parameters and Performance Indicators The primary performance metric extracted from the simulation was the average control delay (s/veh) for each intersection approach and scenario. Delay was selected as the main indicator of operational efficiency because it directly reflects user experience, intersection control effectiveness, and overall network performance. Although other measures such as queue length, average travel speed, Level of Service (LOS), and volume-to-capacity ratio (V/C) can also be derived, the present study focuses on control delay as the measurable output from both field observations and simulation results. These output parameters collectively define the operational performance envelope for the three intersection types, including non-signalized, signalized, and grade-separated intersections, and serve as the basis for constructing the Intersection Selection Chart in Section 3.4. Among them, the average control delay was adopted as the primary criterion for comparing performance and delineating operational zones.

Data Aggregation for Chart Construction For each simulated traffic scenario, the optimal intersection configuration was identified as the one yielding the minimum average control delay. The ten data pairs (N_c, N_0), representing combinations of major-road and minor-road volumes, were subsequently classified into three groups corresponding to the most efficient intersection type, namely non-signalized, signalized, or grade-separated. These classified data points were then plotted in a two-dimensional space, with N_c on the horizontal axis and N_0 on the vertical axis, to visualize their distribution. To delineate the performance boundaries between intersection types, the data were interpolated following the conceptual approach of Lobanov et al. (Lobanov, 1970), generating smooth transition curves that represent the threshold conditions where one configuration begins to outperform another. This empirical adaptation of Lobanov's method provides a quantitative and context-specific decision framework for determining the most suitable intersection type under varying mixed-traffic conditions in Vietnam.

3.4. *Output Processing and Chart Development*

This stage transforms the simulation outputs into a Lobanov-style Intersection Selection Chart by classifying each operating point (N_c, N_0) according to the intersection type that minimizes the average control delay and then delineating the decision boundaries among intersection types. Unlike the original Lobanov model, in which transition boundaries between non-signalized, signalized, and grade-separated intersections were defined empirically under homogeneous, automobile-dominated traffic assumptions, the present study explicitly identifies transition regions through performance-based regime shifts. In mixed-traffic environments, operational efficiency does not degrade linearly with increasing demand. Instead, intersections exhibit nonlinear changes in delay as traffic volumes approach critical levels. Consequently, the classical model lacks an explicit mechanism to determine when one intersection type becomes operationally inferior to another. To address this limitation, transition boundaries in this study are derived by systematically comparing average control delays across all three intersection configurations under identical traffic demand conditions. For each (N_c, N_0) combination, the intersection type producing the minimum average delay is identified as optimal. Transitions occur at operating points where this optimality shifts from one configuration to another, thereby revealing performance-based thresholds that are not explicitly represented in the original model. This procedure enables the detection of missing transition zones and provides a dynamic, data-driven extension of Lobanov's conceptual framework while preserving its intuitive two-dimensional structure.

Data Assembly and Consistency Checks Simulation outputs were consolidated into a structured dataset containing the following parameters:

- N_c: major-road flow (PCU/h).
- N_0: minor-road flow (PCU/h).
- d_{sig}, d_{unsig}, and d_{gs}: average control delays (s/veh) for signalized, non-signalized, and grade-separated intersections, respectively.

For each traffic scenario, the optimal intersection type was determined by:

$$\text{Optimal} = \arg\min \left\{ d_{\text{unsig}}, d_{\text{sig}}, d_{\text{gs}} \right\} \tag{7}$$

Consistency checks ensured that: (1) delays corresponded to identical simulation durations and warm-up periods (Section 3.3); (2) traffic volumes were standardized to passenger car units (PCU), as described in Section 3.2; and (3) each operating point (N_c, N_0) was uniquely associated with a complete set of delay outcomes.

Optimality Rule and Classification For each scenario, the intersection type yielding the minimum average control delay was labelled as optimal. This classification process generated a discrete decision map in the (N_c, N_0) plane, where each point was assigned a categorical label: non-signalized, signalized, or grade-separated. These classes were color-coded to facilitate visual comparison and interpretation.

Boundary Extraction Following the conceptual framework proposed by Lobanov et al. (Lobanov, 1970), transition boundaries between intersection types were extracted through a two-step process. First, local separation lines were computed by identifying pairs of adjacent points belonging to different optimal classes and drawing mid-segments orthogonal to the local delay gradients (Δd). These local segments were then merged to form empirical transition boundaries between intersection types.

The resulting boundaries reflect realistic and monotonic trends consistent with traffic behavior, in which non-signalized intersections dominate under low traffic demand, signalized configurations perform better at medium volumes, and grade-separated designs prevail under high-flow conditions. Unlike prior studies that apply statistical smoothing or functional fitting, this study adopted a transparent midpoint-based construction approach. No statistical smoothing was applied; instead, the midpoint-based construction was retained to ensure transparency and reproducibility.

4. Results and Discussion

Microscopic simulation in PTV VISSIM produced a comprehensive dataset of control delays for three intersection configurations, namely non-signalized, signalized, and grade-separated intersections, under 100 distinct combinations of major-road and minor-road traffic volumes. The resulting average delays ranged from approximately 5–70 s/veh across all scenarios, capturing both undersaturated and near-capacity operating conditions. As expected, delay values increased nonlinearly with total approach flow, reflecting the progressive transition from free-flow to congested states. To facilitate comparison, the delay outcomes were classified according to the optimal intersection type at each operating point, defined by the minimum average control delay. This classification generated a discrete decision map in the (N_c, N_0) plane, which was subsequently used to delineate three operational zones corresponding to the dominant intersection types.

4.1. *Intersection Selection Chart and Regional Characteristics*

Figure 6 presents the Intersection Type Selection Chart for Mixed Traffic in Vietnam, developed from the processed simulation data. The chart delineates three distinct operational zones corresponding to the most efficient intersection types:

- **Zone I** (lower-left region, light blue): predominated by non-signalized intersections, representing low-volume conditions where major-road flow is below approximately 1500 PCU/h and minor-road flow is below 800 PCU/h.
- **Zone II** (central region, light green): dominated by signalized intersections, indicating balanced traffic levels where flow volumes range approximately from 1500–2200 PCU/h on the major road and 800–2200 PCU/h on the minor road.
- **Zone III** (upper-right region, gray): associated with grade-separated intersections, where both major-road and minor-road flows exceed approximately 2200 PCU/h, resulting in saturated or over-saturated operating conditions for at-grade configurations.

Although the boundary extraction in this study relied on midpoint tracing between adjacent points belonging to different optimal classes rather than statistical smoothing, the resulting transitions form clear and interpretable separations among the three operational regimes. The overall pattern illustrated in Figure 6 indicates a hierarchical transition among intersection types as traffic demand increases.

The non-signalized zone (Zone I) occupies a relatively small triangular area in the lower-left corner of the chart, confirming its suitability only under light traffic conditions where conflicting flows remain limited and driver interactions are manageable. Beyond these demand levels, the rapid increase in average control delay, primarily caused by growing minor-road waiting times, renders unsignalized operation inefficient.

The signalized region (Zone II) occupies the largest area of the chart. This finding suggests that signalized intersections provide the most balanced operational performance across a broad spectrum of mixed-traffic conditions typical of urban corridors in Vietnam. Within this range, fixed-time signal control offers sufficient capacity while maintaining acceptable delay levels for both major-road and minor-road approaches. The shape of this region also reflects the ability of signal control to accommodate flow imbalance, which is particularly important under heterogeneous traffic compositions consisting of motorcycles, passenger cars, and light trucks.

At the upper end of the chart, the grade-separated region (Zone III) emerges once both major-road and minor-road flows exceed approximately 2200 PCU/h. Under these demand conditions, even optimized signal timing becomes insufficient to prevent excessive delay and queue spillback, indicating

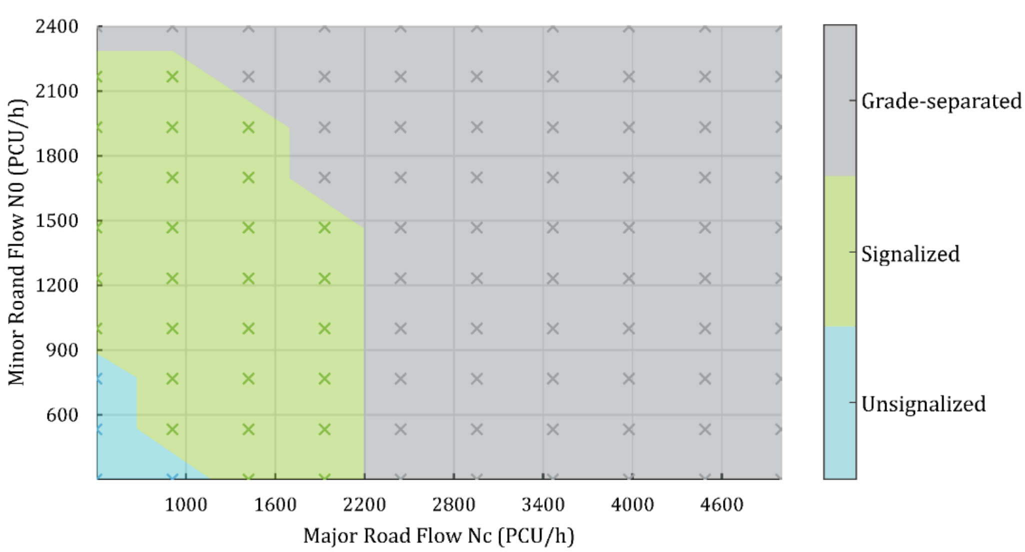

Figure 6: Intersection Type Selection Chart for the studied intersection

the onset of over-saturation in at-grade intersections. Grade-separated facilities therefore become the most effective solution for maintaining throughput and operational safety at high traffic volumes.

When compared with the original Lobanov diagram (Lobanov, 1970), a distinct shift in operational boundaries can be observed. In classical automobile-dominated traffic environments, signalized at-grade intersections can often maintain acceptable delay levels at substantially higher traffic volumes. However, in the proposed mixed-traffic chart, the upper boundary of the signalized regime shifts downward, requiring grade separation when both approaches exceed approximately 2200 PCU/h. This downward shift quantitatively demonstrates how lane-sharing behavior, lateral movements, and reduced lane discipline in motorcycle-dominated traffic streams reduce the effective saturation flow rate and accelerate the transition toward higher-capacity intersection configurations.

4.2. Discussion and Practical Implications

The proposed Intersection Type Selection Chart for Mixed Traffic in Vietnam provides a practical and intuitive tool for urban transport planners and traffic engineers to identify appropriate intersection configurations during the early stages of project planning. By directly relating major-road and minor-road traffic volumes to operational performance, the chart enables rapid screening of intersection control strategies without requiring detailed simulation or capacity analysis for every design alternative.

It should be emphasized that the proposed chart is intended as a control-level and configuration-level decision-support tool rather than a detailed geometric design guideline. In this study, geometric parameters such as lane width, turning radius, channelization, and storage length were intentionally held constant across all simulation scenarios. This modeling choice was made to isolate the effects of traffic demand and intersection type on operational performance and to facilitate the identification of performance-based transition thresholds between non-signalized, signalized, and grade-separated intersections.

While geometric design undoubtedly influences capacity and delay during the detailed design stage, incorporating multiple geometric layouts within the same analysis would confound the interpretation of regime-level transitions, which constitutes the primary objective of this study. Accordingly, the results should be interpreted as guidance on when a change in intersection type or control strategy becomes operationally justified under mixed-traffic conditions rather than as recommendations for specific geometric layouts. Detailed geometric optimization can be conducted subsequently once an appropriate intersection type has been identified using the proposed framework.

Although the analysis is based on a single representative intersection, the proposed framework is designed to be transferable and can be recalibrated for other urban contexts using local traffic data.

Impact of Geometric Design While this study holds geometric parameters constant to isolate the effects of traffic demand, it is important to recognize the influence of geometric design on the proposed framework. Geometric characteristics, including the number of approach lanes, lane widths, and exclusive turning bays, directly affect the saturation flow rate and overall intersection capacity. If an intersection possesses a larger geometric footprint, such as additional approach lanes, its operational capacity increases. Within the

Intersection Selection Chart, this would manifest as an upward and rightward shift of the transition boundaries. Consequently, a geometrically expansive intersection could accommodate higher traffic volumes before transitioning from signalized to grade-separated operation.

Therefore, the chart presented in this study should be regarded as a baseline framework for typical urban multi-lane intersections in Vietnam. The transition boundaries may require adjustment when applied to intersections with substantially different geometric capacities.

In planning practice, the framework can serve as a screening tool to identify locations where intersection upgrades or additional geometric investigations may be warranted. Intersections operating within the signalized or grade-separated regions may be prioritized for control enhancement or future physical intervention, whereas those within the non-signalized region can continue operating with minimal modification. This capability supports more efficient allocation of limited infrastructure resources, particularly in rapidly growing cities such as Ho Chi Minh City and Hanoi, where mixed-traffic conditions dominate and intersection density remains high.

From a planning and design perspective, the chart promotes consistency between projected traffic demand, intersection control strategy, and long-term infrastructure planning without prescribing detailed geometric solutions. For example, planners can evaluate whether a signalized intersection is likely to remain operationally adequate under projected future traffic volumes or whether early right-of-way reservation for future grade separation should be considered.

When integrated into Geographic Information Systems (GIS) or other decision-support environments, the chart can further support corridor-level and network-level prioritization by enabling simultaneous evaluation of multiple intersections within a study area.

Furthermore, the methodology underlying the chart, which links simulated control delay with combinations of traffic demand, may be extended in future studies to evaluate alternative intersection forms, such as Continuous Flow Intersections (CFIs) and Restricted Crossing U-Turn (RCUT) intersections, once geometric configurations are explicitly incorporated into the analytical framework.

Overall, the developed chart bridges the gap between microscopic simulation outputs and practical planning needs by providing a data-driven yet readily interpretable framework for early-stage intersection type selection under heterogeneous traffic conditions.

5. Conclusions

This study developed an Intersection Type Selection Chart for Mixed Traffic in Vietnam through an integrated approach combining empirical data processing, microscopic simulation, and analytical classification based on control delay. The chart provides a practical decision-support framework for determining suitable intersection types, namely non-signalized, signalized, and grade-separated intersections, according to their operational performance under different combinations of major-road and minor-road traffic flows.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

- **Phu Tran:** Lead implementation, conceptualization, data collection, simulation modeling, and result generation
- **Duy-Thoi Do:** Data synthesis, and manuscript writing.
- **Vu-Tu Tran:** Supervision, critical review, research guidance, and manuscript editing.

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