

Article

Capacity Matching Study of Different Functional Lanes at Signalized Intersections

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Abstract

The widening of entrance lanes at urban intersections improves the capacity. However, limited by length, vehicles queuing in different functional lanes often interfere with each other, causing wasted green time. This study analyses turning demand, lane division, and signal timing at short-lane intersections, identifying four types of blockages: left-turn queues overflow blocking straight-ahead, straight-ahead blocking left-turn, right-turn queues overflow blocking straight-ahead, and straight-ahead blocking right-turn. Then, various strategies, including signal timing adjustment, phase sequence, and variable lane functions, are considered. The lane capacity matching rate is calculated, and a model for matching the capacity of different functional lanes at signal-controlled intersections is established. The results show that the matching effect of left-turn is significant, with an improvement of 8.0%, followed by a 7.0% increase in right-turn. The corresponding lane delays are also improved, which demonstrates the effectiveness of the model.

Keywords: traffic engineering; lane saturation; different function lanes; capacity matching rate; blockage type



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1. Introduction

Widening lanes before the stop line at urban signal-controlled intersections can improve capacity, but it may also exacerbate congestion between lanes with different functions. The limited length of widened lanes, combined with high demand for turning movements, can lead to the “short-lane effect”. This occurs when left-turn queues overflow into adjacent straight-ahead lanes, creating traffic bottlenecks. Conversely, straight-ahead traffic can block turning lanes, leading to underutilization of green light time and empty green phases. This issue is especially severe during peak hours, when reduced capacity worsens mutual blockages between traffic flows, resulting in node blockage and potential gridlock. Therefore, it is essential to study the matching of traffic demand and capacity across different functional lanes at intersections to mitigate urban traffic congestion.

The contribution of this paper is the capacity matching of commuting routes, with the focus on matching the capacity of the left-turn and right-turn widened lane with the demand for left-turn and right-turn movements, which differs from the traditional Shared Short Lanes.

2. Literature Review

Research on intersection capacity primarily focuses on modeling and matching strategies. Capacity estimation models, such as the U.S. HCM model, have served as the foundation for classic intersection capacity calculation models [1]. However, these models predominantly address turning lane capacity and the design of lanes or control strategies, with limited analysis of the influencing factors on capacity [2]. Specifically, modeling of expanded lane capacity has evolved from initial independent lane models to probability-adjusted models, covering both right-turn and left-turn lanes. Tian [3] proposed a revised right-turn lane capacity model based on traffic flow characteristics and blockage probability distributions. Leong [4] conducted comparative analyses of the capacity impacts of three types of unconventional right-turn lanes on secondary roads, with subsequent widespread application of probability-based adjustment methods [5]. For left-turn lanes, Zong [6] developed a dual left-turn capacity model based on field data, though it did not consider the mutual blockage effects between lanes. Ma [7] explored the interaction between left-turn and straight-straight-ahead traffic flows, proposing a capacity model that accounts for these interactions and performing sensitivity analyses on green time ratios and short lanes. Cheng [8] examined the effectiveness of a no-left-turn strategy to enhance expanded lane capacity, validated by cellular automata. Wei [9] considered the overflow and blockage probabilities of left-turn lanes, proposing four signal timing models to improve capacity, which were validated by straight-ahead simulations. Additionally, Yu [10] introduced a Markov chain-based short-lane capacity model, demonstrating its effectiveness compared to traditional HCM models.

In terms of capacity matching, scholars have explored the temporal and spatial aspects of node capacity. Most lane-matching studies focus on left-turn and straight-straight-ahead lanes. Bai [11] proposed a left-turn unit-based approach to estimating permitted left-turn capacity with an exclusive lane. Wang [12] investigated the functional lane division at signalized intersections to enhance capacity by adhering to the principle of matching entrance lanes with connecting road lanes. Wu [13] developed a matching model for upstream and downstream node capacity based on optimized left-turn phasing schemes. Addressing individual node capacity matching, Nie [14] proposed various lane layout schemes based on the interrelationships among different flow directions and lane functions, considering constraints such as lane matching and flow balance to demonstrate model feasibility.

From a temporal perspective, research has focused on signal timing plans. Lu [15] proposed a layered modeling approach and framework for optimizing signal control at intersections to describe the intersection states at different levels. Wang [16] proposed a coordinated control plan for phase differences between oversaturated intersections to dynamically match flow spillovers. Yao [17] developed a coordinated optimization model for left-turn lane length and signal timing parameters, which significantly improved intersection performance in empirical tests. Dou [18] analyzed the differences in lane setup, capacity, and signal timing between social and bus lanes, establishing a coordinated optimization model for bus lane capacity. Pallela [19] estimated key parameters such as critical gaps and follow-up times through regression analysis, forming the basis for capacity estimation using the highway capacity manual (HCM), Indo-HCM and Drew's methods.

To quantitatively assess the matching issue, Yang [20] proposed an evaluation method for the degree of intersection capacity matching to quantify traffic blockage resulting from mismatches. Hu [21] introduced the concept and standards for matching turning capacity at intersections, applying it to issues of capacity mismatches.

In conclusion, although intersection capacity modeling [22] is relatively mature, further research is needed for models that consider mutual blockage between traffic flows in

different directions. While studies on node capacity matching have primarily focused on the relationship between upstream roads and entry-exit lanes, further exploration is warranted regarding the matching of different functional lanes. Thus, this study, based on the principles of expanded lane capacity calculation, proposes a capacity matching model for different functional lanes under blocked conditions by analyzing traffic demands at entry lanes. Considering lane saturation, strategies such as extending green time, optimizing phase sequences, and implementing dynamic lane allocation are employed to better match the capacity of different functional lanes. This spatiotemporal approach to lane capacity optimization establishes a theoretical framework for enhancing intersection throughput and rationalizing lane resource distribution, which is essential for mitigating congestion in urban road networks caused by multiple contributing factors.

3. Analysis of Capacity for Different Functional Lanes at Intersections

3.1. Lane Functional State Analysis

Limited by the length of the widened lanes and the green light duration, abnormal vehicle distribution at the intersection entrance lanes may lead to mutual blockage between adjacent lanes. For instance, with an unusually high left-turn demand, the effective green light time may fail to accommodate the flow, potentially resulting in left-turning vehicles completely blocking the straight-ahead lanes.

When the straight-ahead demand exceeds the turning demand, it is possible for the queue of straight-ahead vehicles to exceed the capacity of the left-turning widened lane, thereby blocking it. The same blocking behavior applies to the right-turn widened lane. Based on the differences in traffic demands for various types of lanes, intersections can be categorized into non-blocked and blocked states.

Non-blocked State: Within the same cycle, the flow entering from the common section upstream of the intersection reaches the corresponding functional lanes and can make left turns, right turns, and proceed straight during the effective green light without exceeding the maximum capacity of the widened lanes. In this state, there is no situation where the flow from adjacent lanes blocks each other.

Blocked State: Taking the blockage of straight-ahead traffic by left-turning traffic as an example, as shown in Figure 1, in this scenario, if the left-turn demand is greater than the straight-ahead demand, blockage may occur between the widened and straight-ahead lanes at the end of the effective green light time. This can lead to straight-ahead vehicles being blocked in the common section, resulting in wasted green light time and a reduction in the straight-ahead lane capacity.

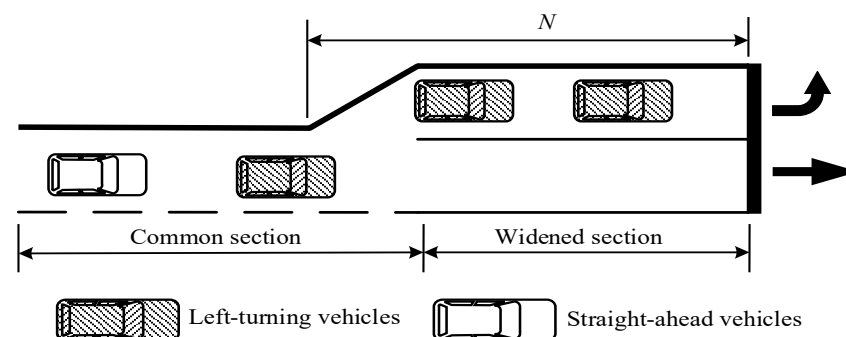


Figure 1. Left-turning widened lane, causing overflow blockage.

3.2. Capacity in Non-Blocked State

The phase sequence begins with the left-turn and is followed by the straight-ahead movement. In the non-blocked state, the number of queuing vehicles in different functional

lanes within the node does not exceed the capacity of the widened lanes. Taking the left-turn and straight-ahead lanes as examples, the effective green time for the left-turn is sufficient to dissipate the vehicles arriving at the node, and the subsequent vehicles arriving at the left-turning widened lane left-turning widened lane will not overflow and block the adjacent straight-ahead lanes, affecting the passage of vehicles in the straight-ahead phase; simultaneously, straight-ahead vehicles can be dispersed within the phase passage time, and there is no situation where queuing vehicles block the widened section, with the right-turn being analogous.

Therefore, after determining the basic signal timing plan and the type of widened lane at the signal-controlled intersection, the capacity of different functional lanes in the import road in the non-blocked state is jointly determined by the effective green time of the phase and the lane saturation flow [23]. This study considers that the right-turn widened lane is subject to signal control, and its green ratio is determined by the flow of non-motorized vehicles, pedestrians, and the number of right-turn vehicles.

3.2.1. Capacity of Left-Turning Widened Lane Left-Turning Widened Lanes

The existence of widened lanes leads to non-uniformity in turning traffic flow; hence, the calculation model for the capacity of left-turn lanes is presented in Equation (1).

$$C_L^0 = \begin{cases} S_L^1 \frac{g_{Le}}{c}, & g_{Le} \leq T_L \\ S_L^1 \frac{T_L}{c} + S_L^2 \frac{g_{Le} - T_L}{c}, & g_{Le} > T_L \end{cases} \quad (1)$$

3.2.2. Capacity of Straight-Ahead Lanes

The parameters of the traffic capacity matching model are shown in Table 1. Under non-blocked conditions, the calculation model is the same as that for the left-turning widened lane left-turning widened lanes, as shown in Equation (2).

Table 1. Parameters and variables of the traffic capacity matching model.

Symbol	Description
C_i^0	the capacity of lane i in the non-blocked state at the node, $i = L, T, R$, represents left-turn, straight-ahead or right-turn, ($\text{pcu} \cdot \text{h}^{-1}$)
S_i^1, S_i^2	S_i^1 is the saturation flow of phase i in the unblocked state; S_i^2 is the saturation flow entering the widened section in non-blocked state, ($\text{pcu} \cdot \text{h}^{-1}$)
T_i	the dissipation time of the maximum queue in the widened section, (s)
g_{ie}	effective green time for lane i , (s)
c	signal cycle time, (s)
N_{TL}^3	number of vehicles the independent straight lane can accommodate during the remaining green time after blockage occurs
C_i^d	the potential capacity of independent lane i after blockage occurs, ($\text{pcu} \cdot \text{h}^{-1}$)
C_i^2	blocked capacity of lane i , ($\text{pcu} \cdot \text{h}^{-1}$)
λ_i	lane saturation i
C_i^3	possible capacity of lane i after implementing the matching strategy, ($\text{pcu} \cdot \text{h}^{-1}$)
m_i	number of lanes in the widened section area
C_i^m	matched capacity of lane i , ($\text{pcu} \cdot \text{h}^{-1}$)
M_i	capacity matching rate for the lane i

$$C_T^0 = \begin{cases} S_T^1 \frac{g_{Te}}{c}, & g_{Te} \leq T_T \\ S_T^1 \frac{T_T}{c} + S_T^2 \frac{g_{Te} - T_T}{c}, & g_{Te} > T_T \end{cases} \quad (2)$$

This study defines the effective green time for the right-turn as the product of the average number of times vehicles yield per unit time and the cycle length, transforming the uncontrolled situation into one controlled by a red light. The specific calculation model is presented in the following Equation (3).

$$g_{Re} = nc \quad (3)$$

where n is the average number of times vehicles yield per unit time at the intersection, obtained from historical data based on the type of intersection.

3.2.3. Capacity of Right-Turn Widened Lanes

The model for the right-turn widened lane is similar to that of the left-turn, and the calculation model for the capacity of the right-turn lane is presented in Equation (4).

$$C_R^0 = \begin{cases} S_R^1 \frac{g_{Re}}{c}, & g_{Re} \leq T_R \\ S_R^1 \frac{T_R}{c} + S_R^2 \frac{g_{Re} - T_R}{c}, & g_{Re} > T_R \end{cases} \quad (4)$$

3.3. Capacity in Blocked State

3.3.1. Widening Lane Blockage Analysis

Consider a signal-controlled intersection with both left- and right-turn widened lanes, as depicted in Figure 2. Suppose the widened lanes can accommodate up to N standard sedans per lane. By analyzing the behavior of different turning traffic flows and their mutual blocking with adjacent straight-ahead traffic, the blocking phenomena are categorized into four types for discussion:

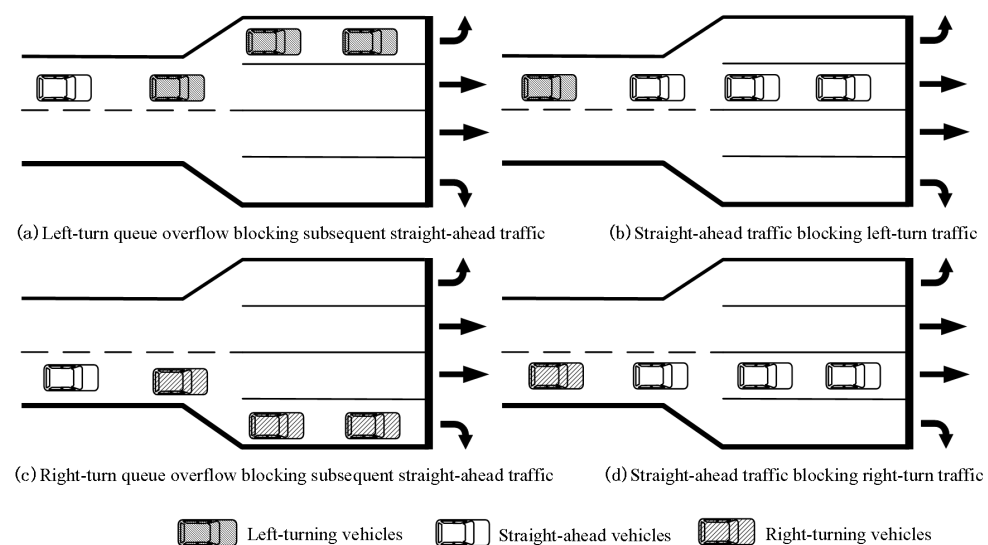


Figure 2. Types of lanes blocked by different functions.

- (1) Left-turn queue overflow blocking straight-ahead traffic, see Figure 2a.

When there is a high demand for left-turning traffic, the flow at the end of the effective green light cannot completely clear the lane, resulting in queuing. If at any moment the queued vehicles exceed the capacity of the widened lane, an overflow occurs that blocks the straight-ahead traffic, causing vehicles on the adjacent straight-ahead lane to lose their right of way. This is when the number of queued left-turn lanes exceeds $N + 1$, spilling over onto the common section.

- (2) Straight-ahead traffic blocking left-turn traffic, see Figure 2b.

When there is a queue in the straight-ahead lane that exceeds the capacity of the adjacent left-turning widened lane left-turning widened lane, it may block the normal passage of left-turning traffic. This occurs when the number of queued vehicles in the widened lane area exceeds $N + 1$, preventing left-turning vehicles from entering the left-turn widened section and requiring them to wait until the straight-ahead queue clears.

(3) Right-turn queue overflow blocking straight-ahead traffic, see Figure 2c.

Due to the influence of non-motorized vehicles and pedestrians, right-turning vehicles stop to yield to pedestrians, leading to queuing. When there is a high demand for right-turning traffic, it may overflow and stagnate on the adjacent straight-ahead lane at some point, causing a blockage for subsequent straight-ahead traffic.

(4) Straight-ahead traffic blocking right-turn widened lanes, see Figure 2d.

When the evacuation rate of the straight-ahead lane is less than the arrival rate, a queue may accumulate, and the $(N + 1)$ th consecutive straight-ahead vehicle to arrive will block the right-turn widened lane, causing subsequent right-turning vehicles to be stranded on the straight-ahead lane.

3.3.2. Blocking Capacity

(1) Type 1: Left-turn queue overflow blocking subsequent straight-ahead traffic

If the intersection experiences only one type of blockage, considering the existence of independent straight-ahead lanes that are not blocked, they can continue to operate. If two types of blockages occur, there are no independent lanes left, and the number of vehicles that can pass straight-ahead the independent straight-ahead lane during the remaining effective green time is calculated using Equation (5).

$$N_{TL}^3 = \begin{cases} 0 & \alpha_T \leq 0 \\ \alpha_T S_T^3 & \alpha_T > 0 \end{cases} \quad (5)$$

where S_T^3 is the saturation flow of the independent straight-ahead lane; α_T is a temporary variable determined by the earliest left-turn queuing time and the latest queuing overflow time.

The calculation formula for the throughput capacity of the straight-ahead lane after blockage is given by Equation (6).

$$C_{TL}^d = \min \left[N_{TL}^1 + N_{TL}^2 + N_{TL}^3, S_T^1 \frac{g_{Te}}{c} \right] \quad (6)$$

where N_{TL}^1 is the number of straight-ahead vehicles arriving during a cycle from the start of queuing in the straight-ahead area to the start of queuing in the left-turn widened section; N_{TL}^2 is the number of vehicles that pass the stop line of the straight-ahead lane up to the point where left-turn blockage occurs.

The basic model parameters for the throughput capacity of the straight-ahead lane during blockage are shown in Figure 3. The occurrence of blockage in the import lane is a process from a non-blocked state to a blocked state, and its capacity includes two parts: the non-blocked state and the blocked state, as shown in Equation (7).

$$C_{TL}^2 = P_{TL}(N_{TL}^1) P_{TL}(N_{TL}^2) \left[P_{LbT} C_{TL}^d + (1 - P_{LbT}) C_T^0 \right] \quad (7)$$

where $P_{TL}(N_{TL}^1)$ is the probability that the number of straight-ahead vehicles passing during a cycle from the start of queuing in the straight-ahead area to the appearance of queuing in the left-turn widened section is N_{TL}^1 ; $P_{TL}(N_{TL}^2)$ is the probability that the number

of vehicles that can leave the straight-ahead area widened section after time φ_{T1} is N_{TL}^2 ; P_{LbT} is the probability that left-turn queuing overflow blocks the straight-ahead from time t_0 to t_1 .

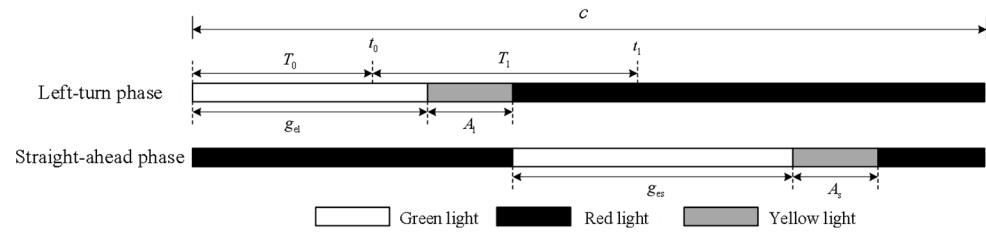


Figure 3. Model parameters for throughput capacity of straight-ahead lanes.

(2) Type 2: Straight-ahead traffic blocking left-turning widened lane left-turning widened lanes

The derivation process for the blocked throughput capacity of left-turn traffic is the same as for straight-ahead traffic. The difference lies in the fact that after blockage occurs, there are no independent left-turn (or right-turn) lanes to disperse vehicles. Taking the blocked throughput capacity of left-turn traffic as an example, the calculation model after blockage is given by Equation (8).

$$C_L^d = \min \left[N_L^1 + N_L^2, S_L^1 \frac{g_{Le}}{c} \right] \quad (8)$$

where N_L^1 is the number of left-turn vehicles arriving during a cycle from the start of queuing in the left-turn widened section to the appearance of queuing in the straight-ahead area; N_L^2 is the number of vehicles that pass the stop line of the left-turning widened lane up to the point where straight-ahead traffic blockage occurs.

The calculation model for the blocked throughput capacity of the left-turning widened lane is given by Equation (9).

$$C_L^2 = P_L(N_L^1) P_L(N_L^2) \left[P_{TbL} C_L^d + (1 - P_{TbL}) C_L^0 \right] \quad (9)$$

where P_{TbL} is the probability that straight-ahead queuing vehicles block the left-turning widened lane from time t_0 to t_1 .

(3) Right-turn queue overflow blocking subsequent straight traffic

When blockage occurs between right-turn vehicles and the adjacent straight-ahead lane, the blocked throughput capacity of the straight-ahead lane is the same as when left-turn queuing overflows and blocks, which can be represented by Equation (10).

$$C_{TR}^2 = P_{TR}(N_{TR}^1) P_{TR}(N_{TR}^2) \left[P_{RbT} C_{TR}^d + (1 - P_{RbT}) C_T^0 \right] \quad (10)$$

where $P_{TR}(N_{TR}^1)$ is the probability that the number of straight-ahead vehicles passing during a cycle from the start of queuing in the straight-ahead area to the appearance of queuing in the right-turn widened section is N_{TR}^1 ; $P_{TR}(N_{TR}^2)$ is the probability that the number of vehicles that can leave the straight-ahead area widened section after time φ_{T1} is N_{TR}^2 ; P_{LbT} is the probability that right-turn queuing overflow blocks the straight-ahead from time t_0 to t_1 .

(4) Type 4: Straight-ahead traffic blocking right-turn widened lanes

The blocked throughput capacity of the right-turn widened lane is similar to that of the left-turn lane, and the model can be represented by Equation (11).

$$C_R^2 = P_R(N_R^1)P_R(N_R^2)[P_{TbR}C_R^d + (1 - P_{TbR})C_R^0] \quad (11)$$

where P_{TbR} is the probability that straight-ahead queuing vehicles block the right-turn widened lane from time t_0 to t_1 .

4. Capacity Matching of Different Functional Lanes

4.1. Matching Process and Strategy

4.1.1. Lane Saturation

The imbalance between traffic demand for different turning movements at an intersection and the capacity of corresponding lane functions can result in congestion and blockages. This study quantifies the matching conditions of different functional lanes based on commuter lane saturation, providing a foundation for optimizing lane capacity allocation.

The lane saturation λ refers to the ratio of the actual traffic flow to the capacity under non-blocked conditions, and its value satisfies $\lambda \geq 0$. It can measure the traffic efficiency of each lane at the node under blocked conditions. The larger the value, the more severe the blockage problem. If its value is greater than 1, it indicates that the actual capacity of the lane is not enough to accommodate the input traffic flow, and adjacent lanes will definitely produce mutual blocking behavior. The calculation model is shown in Equation (12).

$$\lambda_i = \frac{C_i}{C_i^0} \quad (12)$$

where C_i represents the actual capacity of each lane at the node entrance; C_i^0 represents the actual capacity of the lane under non-blocked conditions.

4.1.2. Process and Strategy

The specific steps of the capacity matching process are as follows:

Step 1: In the non-blocked state, calculate the capacity of different lane functions of the node. The capacity of each turning lane is calculated according to the green ratio, the number of lanes, and the saturated flow rate, etc.; secondly, the lane saturation is calculated according to Equation (12), as the basis for judging the implementation of the matching strategy.

Step 2: Check whether the matching criteria are met.

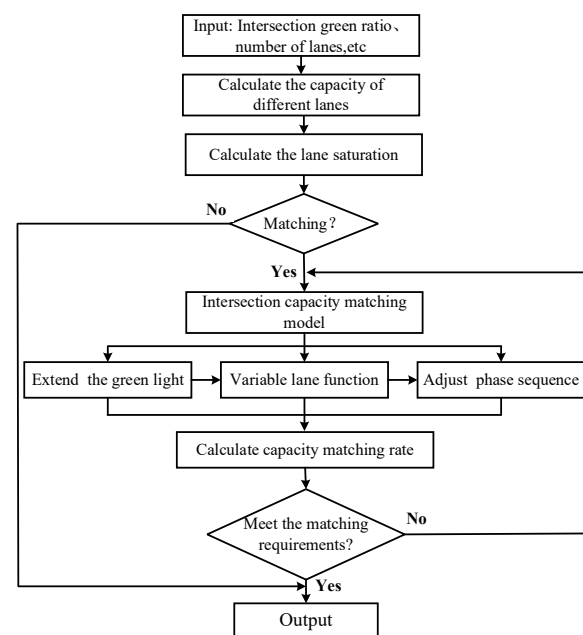
Step 3: Based on the predefined parameters α and β , discuss the matching strategy across different intervals of commuter lane saturation, and set the parameter values to $\alpha = 1.0, \beta = 1.5$ [14].

- (1) When the lane saturation λ is less than α and greater than 0.7, it indicates that the input flow is lower than the saturation state, but there is an occasional problem of mutual blocking of vehicles, so it can be considered to extend the green time of the lane with high demand;
- (2) When the lane saturation λ is greater than α and less than β , the traffic flow exceeds the saturation flow in the non-blocked state, and it is difficult to alleviate the mutual blockage phenomenon of different traffic flows by extending the green time, so the variable lane scheme is implemented;
- (3) When the lane saturation λ is greater than β , the intersection blockage problem is serious. By adjusting the phase sequence, that is, adopting the single-port release strategy, the blockage can be alleviated at a certain flow rate. The specific matching strategy is shown in Table 2.

Table 2. Blockage level, solutions for various lanes.

Lane Saturation λ	Matching Strategy
$0.7 \leq \lambda < 1.0$	extend green light time
$1.0 \leq \lambda < 1.5$	extend green light time and make the lane function variable
$\lambda \geq 1.5$	adjust phase sequence
Lane saturation λ	Matching strategy

Step 4: Calculate the matching rate of capacity, determine whether the matching standard is reached, and finally output the result. See Figure 4 for the specific process.

**Figure 4.** Capacity matching process.

4.2. Capacity Matching

4.2.1. Model Assumptions

Right-turn widened lanes may be under signal control or may operate without control, considering the impact of pedestrians and non-motorized traffic when uncontrolled [24].

Vehicle flows arrive at the node following a Poisson distribution and are independent of each other.

In the event of a blockage involving two streams of traffic, vehicles within the widened lane section affected by the blockage are neglected.

When two types of blockages occur simultaneously, it is assumed that the blockage that occurs first has a minimal impact on subsequent blockages.

The saturation flow rate at the node is stable across all cycles within a given time period.

All vehicles arriving at the node are converted into standard passenger cars for calculation purposes.

4.2.2. Matching Rate of Lane Capacity

In the non-blocked state of the approach, the flow from the road section matches the output flow of the different functional lanes at the node entrance, indicating minimal interaction effects between different traffic streams. Conversely, in a blocked state, the input flow from the road section exceeds the capacity of the widened lanes. The current

signal timing scheme and vehicle layout are insufficient to disperse the flow, meaning the node's inflow exceeds outflow, leading to severe blockage within the approach lanes. To describe the implementation of matching strategies and to evaluate the balance between node outflow and input, a capacity matching evaluation indicator is introduced, namely, the matching rate.

The capacity matching rate is the ratio of the capacity of a lane in the widened section after the implementation of matching strategies to the actual input flow of the turning movement from the common section, as shown in Equation (13). It is used to assess the degree of matching between the road section and the node entrance, with a value closer to 1 indicating a suitable matching strategy and the effective dispersion of traffic flow in the widened section lanes.

$$M_i = \frac{m_{0i}C_i^m}{m_a p_i C_a} \times 100\% \quad (13)$$

where m_{0i} is the number of left-turn, straight-ahead, and right-turn lanes in the widened section area; m_a is the number of lanes in the common area; p_i is the proportion of the flow for a specific turning movement in the common area, obtained from historical traffic data; C_a is the actual input flow to the common section.

4.2.3. Capacity Matching Model

(1) Straight-ahead lane capacity matching model

Taking the blockage of straight-ahead traffic by left-turning vehicles as an example, when the queue of left-turning vehicles overflows and obstructs the straight-ahead movement, a matching strategy [25] is implemented for the widened left-turn lane to alleviate the congestion. The number of left-turn vehicles that can potentially pass after the matching is given in Equation (14).

$$C_L^3 = \begin{cases} m_L S_L^3 g_{LE}, & \lambda_L < \alpha \\ m_L S_L^3 (g_{LE} - \varphi_{L1}), & \alpha \leq \lambda_L < \beta \\ m_L S_L^3 g_e, & \lambda_L \geq \beta \end{cases} \quad (14)$$

where S_L^3 is the saturation flow of the left-turning widened lane after implementing the matching strategy; g_{LE} is the extended green time for the left-turning widened lane; φ_{L1} is the time from the earliest possible blockage in the left-turning widened lane to the latest blockage in the adjacent straight lane.

At this point, the capacity of the left-turn lane consists of two parts: the non-blocked state and the blocked state with the matching strategy applied. Therefore, the matched capacity of the left-turning widened lane is shown in Equation (15).

$$C_L^m = P_L(N_L^1)P_L(N_L^2)(1 - P_{bTL})C_L^0 + C_L^3 \quad (15)$$

Then, after the blockage dissipates, the straight-ahead lane that was blocked becomes passable, and the capacity of the straight-ahead lane is shown in Equation (16).

$$C_T = m_T S_T^3 \frac{(g_{Te} - g_{TI})}{c} + \mu_T C_T^0 \quad (16)$$

where C_T is the matched capacity of the straight lane after implementing the matching strategy when blocked by left-turning traffic; S_T^3 is the saturation flow of the straight-ahead lane after the implementation of the matching strategy; g_{TI} is the time from the green light illumination of the straight-ahead phase to the implementation of the matching strategy; μ_T is the capacity loss coefficient of the straight-ahead lane after the blockage.

The case of right-turning vehicles blocking adjacent straight-ahead lanes, or both left-turning and right-turning vehicles blocking adjacent straight-ahead lanes at the same time, that is, the situation where the straight-ahead lane is blocked, can all be considered using the above matching model to estimate the capacity of the straight-ahead lane.

(2) Turning widened lane capacity matching model

Taking the blockage of the left-turning widened lane by straight-ahead traffic as an example, when the queue of straight-ahead vehicles exceeds the lane's capacity, optimization is required to alleviate the blockage. The matching strategy mirrors that used when left-turning traffic blocks straight-ahead movement. After applying the strategy, the number of vehicles that can potentially pass through the straight-ahead lane is given in Equation (17).

$$C_T^3 = \begin{cases} m_T S_T^3 g_{TE}, & \lambda_T < \alpha \\ m_T S_T^3 (g_{TE} - \varphi_{T1}), & \alpha \leq \lambda_T < \beta \\ m_T S_T^3 g_e, & \lambda_T \geq \beta \end{cases} \quad (17)$$

where S_T^3 is the saturation flow of the straight-ahead lane after the implementation of the matching strategy; g_{TE} is the extended green light time for the straight-ahead lane; φ_{T1} is the time from the earliest possible blockage of the straight-ahead lane in the widened section area to the latest blockage of the adjacent left-turn lane.

At this point, the matched capacity of the straight-ahead lane includes two parts: the non-blocked state and the blocked state with the matching strategy applied. Therefore, the matched capacity model of the straight-ahead lane is shown in Equation (18).

$$C_T^m = P_T(N_T^1)P_T(N_T^2)(1 - P_{bTL})C_T^0 + C_T^3 \quad (18)$$

Then, after the blockage of the straight-ahead lane is cleared, the capacity of the left-turning widened lane is shown in Equation (19).

$$C_L = m_L S_L^3 \frac{(g_{Le} - g_{Li})}{c} + \mu_L C_L^0 \quad (19)$$

where C_L is the matched capacity of the left-turning widened lane after the implementation of the matching strategy when blocked by straight-ahead traffic; S_L^3 is the saturation flow of the left-turn lane after the implementation of the matching strategy; g_{Li} is the time from the green light illumination of the left-turn phase to the implementation of the matching strategy; μ_L is the capacity loss coefficient of the left-turn lane after the blockage, determined by the remaining effective green light time of the original phase.

5. Case Analysis and Verification

5.1. Data Collection

The intersection of Jin Qiao Road and Xin Jin Qiao Road in Pudong New Area, Shanghai, was selected for analysis, with the northbound approach of Xin Jin Qiao Road being the subject of validation for the capacity matching model. The upstream section of this approach consists of 2 lanes, which expand to 4 lanes in the widened section, including 2 straight-ahead lanes and one each for left-turn and right-turn widened lanes. The classification of lane functions is shown in Figure 5.

During peak hours, there is a significant demand for turning movements at this approach, and the widened lane length is only 50 m, making it prone to queuing overflow and blockage of straight-ahead traffic by left-turning and right-turning vehicles. Compared to other time periods, the evening peak hour better meets the requirements of the scenarios

studied by our model. Moreover, the approach meets the requirements of the capacity matching model, accommodating both left-turn and right-turn widening patterns.

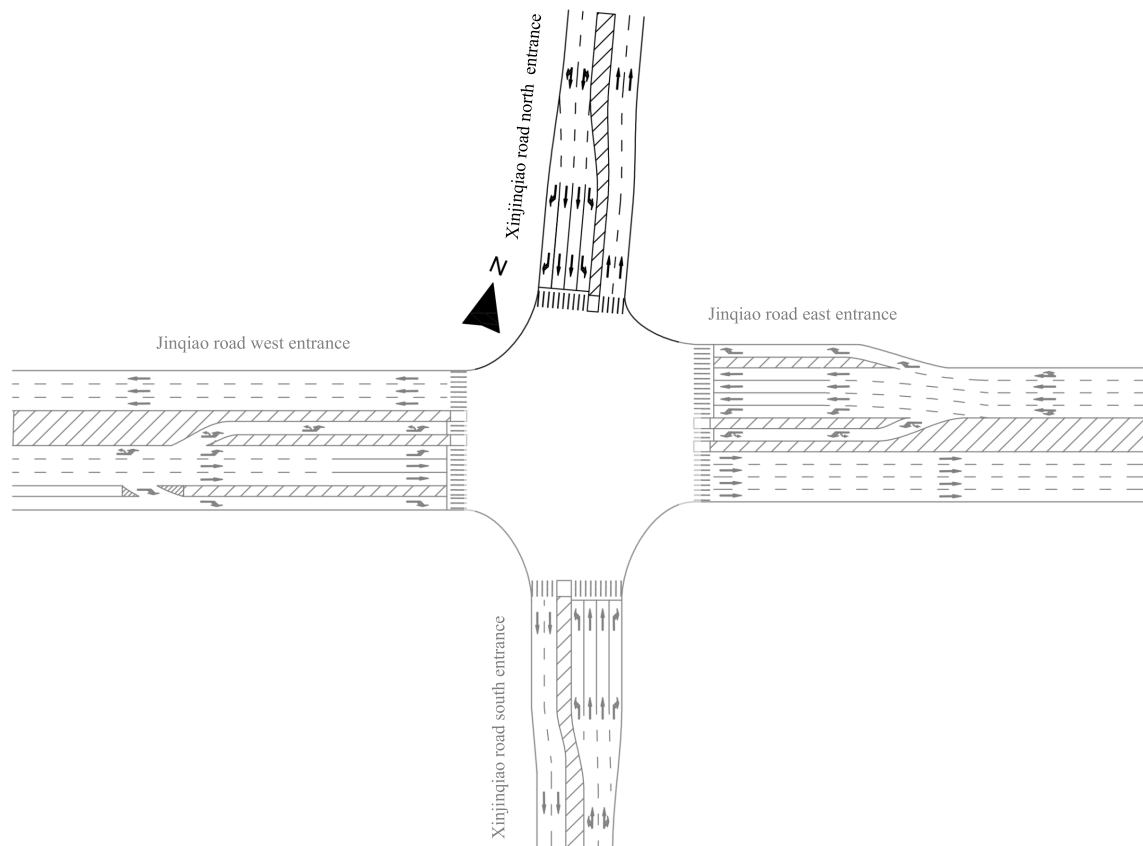


Figure 5. Intersection lane functional classification.

This intersection is a four-phase signal-controlled intersection with a cycle time of 180 s. The green signal ratio for the northbound straight-ahead lane is 0.25, and for the left-turn lane, it is 0.17. The green light interval time is 5 s. The flow data and signal timing schemes for each approach during the evening peak hour are presented in Table 3, which are the inputs of the model.

Table 3. Flow data and signaling schemes of the intersection.

Parameter	North Import			South Import		
	Left-Turn	Right-Turn	Straight-Ahead	Left-Turn	Right-Turn	Straight-Ahead
flow/(veh/h)	201	715	195	305	262	542
Green time/(s)	30	—	45	30	—	45
Yellow light/(s)	3	—	3	3	—	3

5.2. Results Discussion

To verify the benefits of the capacity matching model, an analysis of the trend of lane capacity matching under different traffic demands was conducted by increasing the flow of the input road section, that is, loading 20%, 40%, 60%, and 80% on the basis of the actual flow, and conducted simulation experiments using Vissim simulation software (Vissim 8.0).

The saturation flow rates for left-turn, right-turn, and straight-ahead phases are 1650, 1700, and 3600 veh/h, respectively. Capacity was calculated using Equations (1), (2), and (4),

and the lane saturation was further calculated using Equation (12) to obtain the capacity of each lane at the northbound approach in a non-blocked state, with results shown in Table 4.

Table 4. Nodal flow data and signaling schemes.

Lane Function	Capacity in Non-Blocked/(veh/h)	Flow Increases/(%)				
		0	20	40	60	80
Left-turn	275	0.73	0.88	1.02	1.17	1.32
Straight-ahead	900	0.79	0.95	1.11	1.27	1.43
Right-turn	359	0.54	0.65	0.76	0.87	0.98

5.2.1. Analysis of Capacity for Different Functional Lanes

From Table 4, it can be seen that when the actual flow increased to 20% of the original, the lane saturation was less than 1, with left-turn and straight-ahead values being greater than right-turn. This indicates that the probability of mutual blockage between left-turn and straight-ahead movements is gradually increasing, while the right-turn movement is not signal-controlled. As the flow increased varied from 40% to 80%, the lane saturation for left-turn and straight-ahead movements increased to 1 and continued to rise, while the right-turn movement approached saturation.

Accordingly, the following strategies were implemented for different traffic demands: First, when the flow increase was 0–20%, the signal timing for left-turn and straight-ahead phases was optimized, and the green light time was readjusted based on the actual flow. Second, when the flow increase was 40% and 60%, and the lane saturation was greater than 1, a variable lane scheme was considered first. If the capacity matching result was below 50%, a combination strategy of extending green light time and variable lane function was considered. Third, when the flow increase was 80%, the blockage approached 1.5. Matching was conducted according to the previous strategy, and if the matching result was below 40%, adjusting the phase sequence and changing the intersection to a single-lane release form was considered.

Following the aforementioned matching strategies, the comparison of capacity before and after matching for different functional lanes at the northbound approach, with flow increases of 0%, 20%, 40%, 60%, and 80%, is shown in Figure 6.

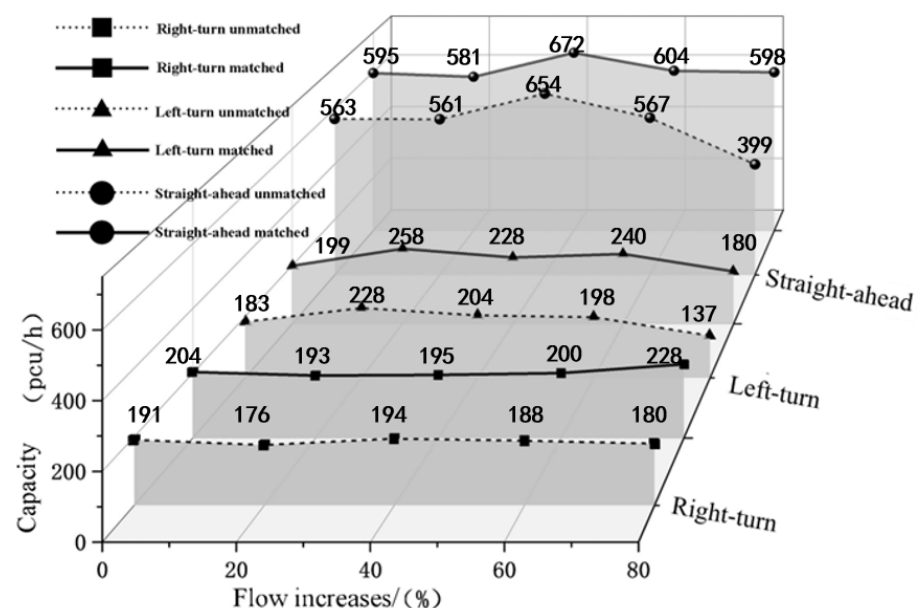


Figure 6. Comparison of capacity before and after matching of different functional lanes.

From Figure 6, it can be seen that before the implementation of the capacity matching strategy, the capacity of different functional lanes at the approach showed an overall downward trend with the increase in flow. The straight-ahead lane, which was most affected by the blockage of adjacent widened lanes, showed a significant fluctuation in capacity, reaching a maximum of 199 pcu/h. The left-turn lane was next, with an average increase of 31 pcu/h, while the right-turn lane showed a gentle increase, averaging 18 pcu/h. After adopting the matching strategy under different traffic demands, the specific results of the increase in capacity for each lane are shown in Table 4.

From Figure 6 and Table 5, it can be seen that when the flow increase was between 0 and 60%, the implementation of the matching measures resulted in an average increase in capacity of 5.8% for right-turn, 13.8% for left-turn, and 4.6% for straight-ahead movements. Compared with the straight-ahead lane, the capacity of the widened lanes was more affected by blockage; especially when the flow increase was 80%, the actual input flow of the straight-ahead lane was severely blocked by the adjacent widened lanes, resulting in only 300 pch/h being passable, which significantly increased the matching rate of the straight-ahead lane after matching.

Table 5. Capacity improvement before and after lane matching.

Lane Function	Flow Increases/(%)				
	0	20	40	60	80
Left-turn	13	17	1	12	48
Straight-ahead	17	30	24	42	42
Right-turn	33	20	18	37	199

5.2.2. Improvement in Capacity Matching Rate for Different Functional Lanes

Based on Equation (13), the capacity matching rate before and after the implementation of the strategy for different functional lanes was calculated, with results shown in Figure 7. As the flow increases, the matching rate for different functional lanes generally shows a downward trend, mainly because the input flow has far exceeded the maximum capacity of the lanes themselves. When the flow increases again, the capacity matching rate will tend to a stable value.

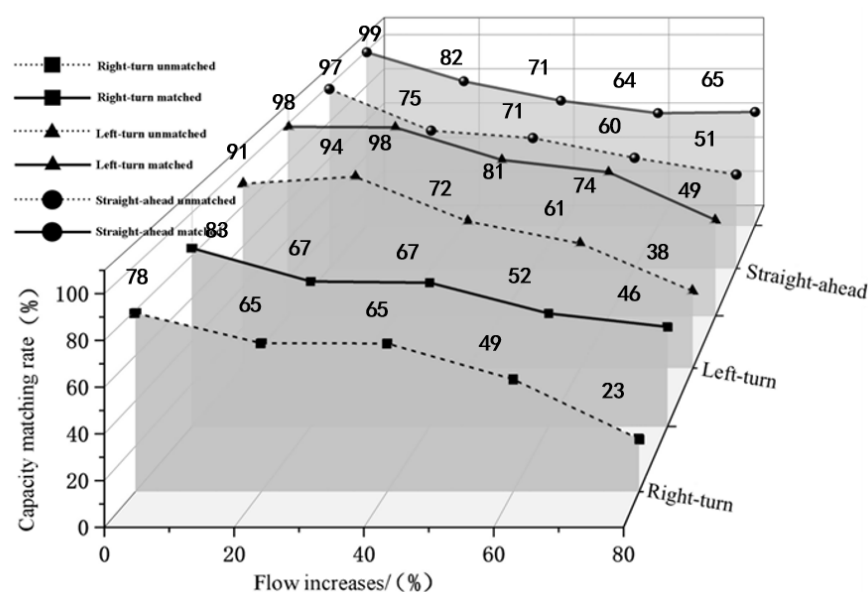


Figure 7. Capacity matching ratio trends before and after functional lane matching.

Specifically, when the flow increase ranges from 0 to 60%, compared with before the matching strategy was implemented, the benefits of the lane capacity matching model have increased. The left-turn and right-turn widened lanes are greatly affected by the matching strategy, with the matching rate fluctuating significantly, reaching a maximum of 20%. The straight-ahead lane matching rate is relatively stable, averaging 4.6%. Overall, the average matching rate for the left-turning widened lane increased by 8.0%, the straight-ahead lane by 3.1%, and the right-turn widened lane by 3.0%.

When the flow increase is 80%, the actual capacity of different functional lanes decreases significantly. Therefore, after the implementation of the matching strategy, the increase in the capacity matching rate is the most significant. Compared with before matching, the right-turn capacity matching rate increased by 23.3%, and the left-turn and straight-ahead lane matching rates increased by 10%.

5.2.3. Improvement in Control Benefits for Different Functional Lanes

The average queuing delay of the lanes is used as an indicator to evaluate the overall operational performance of the approach. The change in the average queuing delay for different functional lanes obtained straight-ahead simulation is shown in Figure 8 and Table 6.

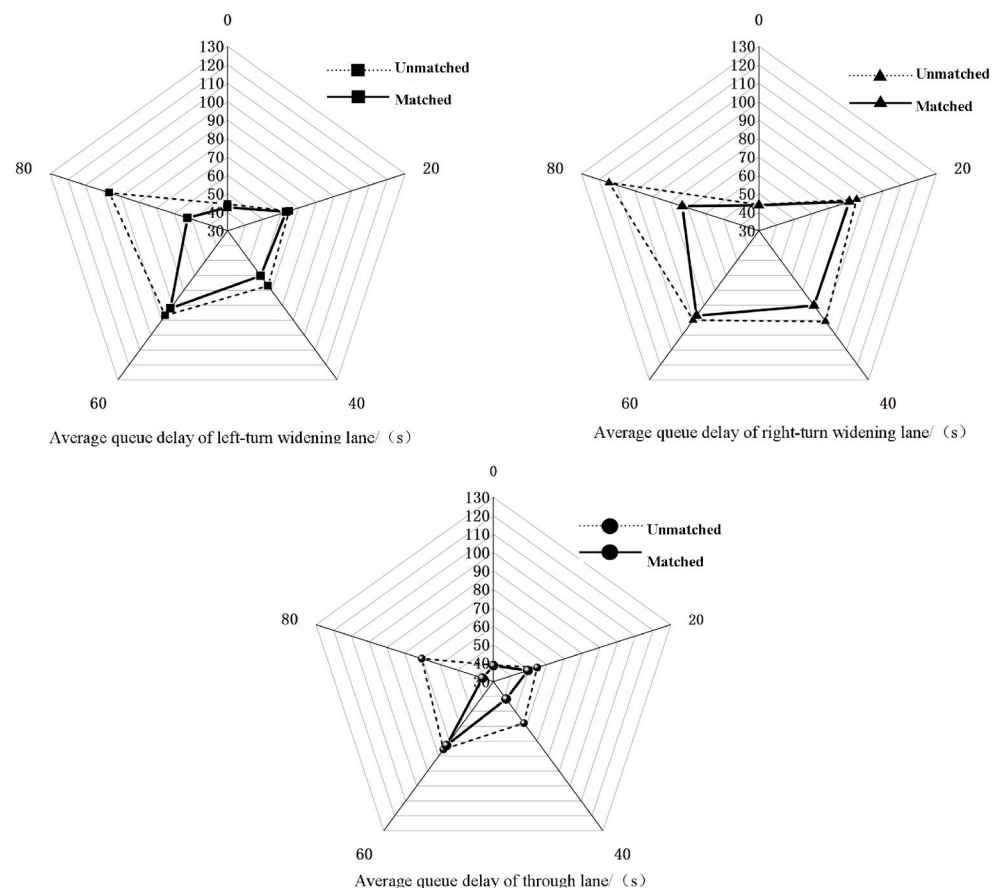


Figure 8. Comparison of lane average queuing delay results.

Affected by the matching strategy, the average queuing delay time of the lanes shows a varying degree of reduction with the increase in flow. Compared with the straight-ahead lane, the reduction in the widened lanes is significant. When the flow increase is 80%, the reduction in the average queuing delay for different functional lanes is the most significant, with left-turn and straight-ahead lanes reducing by 40% and right-turn by 30%. Next, when the flow increase is 40%, the reduction in the average queuing delay for the straight-ahead lane is significant at 28%, while the left-turn and right-turn reductions are both

10%, with other increases being less significant. When the flow increase is 80%, the overall reduction trend is significantly higher than other flow increases, indicating that as traffic demand increases, the probability of mutual blockage between different functional lanes increases. The capacity matching model of this study can effectively reduce or even avoid these impacts.

Table 6. Lane average queuing delay improvement before and after lane matching.

Lane Function	Flow Increases/(%)				
	0	20	40	60	80
Left-turn	0.3	4.1	10.5	3.0	41.3
Straight-ahead	1.8	1.7	6.8	4.9	44.1
Right-turn	0.3	5.2	16.2	2.7	34.3

6. Conclusions

This study addresses the capacity of different functional lanes at signalized intersections, considering factors such as traffic demand, lane division, and signal timing. A capacity estimation model was developed to account for blockages between widened lanes and adjacent straight lanes. Based on this, a capacity matching model was established, which calculates the matching rates to optimize lane utilization.

From a spatiotemporal perspective, the study investigated the capacity matching between intersection approaches and widened segments. Strategies for matching capacity, such as adjusting signal timing, phase sequences, and lane function variability, were implemented. The effectiveness of the capacity matching model was validated by comparing the changes in capacity before and after matching, the capacity matching rates for different functional lanes, and the average queue delay. The results indicated significant improvements, especially under increasing traffic demand.

However, when adjacent intersections on urban roads are too close, the effectiveness of capacity matching for different functional lanes at intersections can be limited, particularly under short-term peak traffic conditions such as commuting periods. This may result in the transfer of blockage to other areas. Therefore, it is essential to consider the capacity matching of upstream and downstream intersections and even broader areas. This can be achieved by using variable speed green waves to guide traffic flow, ensuring capacity matching along multiple intersections on a given route. This broader scope of research will be a key focus for future studies.

Additionally, our study focused on intersections with two straight-through lanes. Whether our matching strategy is applicable to other intersections, especially those with only one straight-through lane requires further investigation. Simultaneously, we need to incorporate how pedestrians and non-motorized vehicles influence traffic to enrich our research scope.

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