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Research Article

A Method for Determining the Capacity of an Exclusive Left Lane with a Permitted Phase under Nonstrict Priority

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A new method has been developed for estimating the capacity of an exclusive left lane with a permitted phase under nonstrict priority. Different from maneuvers under strict priority, these left-turning vehicles were released in the form of a left-turn group. A field survey was first conducted to explore the maximum number of vehicles in a left-turn group, and the releasing process of the permitted left turns. The observations revealed that (1) the maximum number is related to the intersection geometry and (2) the releasing process includes two stages: the first left-turn group crossing at the beginning of a permitted phase and the following left-turn groups crossing using gaps provided by opposing right turns. Next, a method based on probability theory and these observation results were applied to estimate the capacity of an exclusive left lane. The procedure contains two stages and eight steps. Finally, the estimation of the left-turn capacity using the proposed model was validated by comparing the capacity from the strict priority and actual maximum volumes.

1. Introduction

At a signalized intersection, permitted left turns, either from shared lanes or from exclusive lanes, will have serious impacts on intersection operations. According to traffic laws, vehicular traffic turning left and facing a permitted phase must yield the right-of-way to oncoming traffic; however, this situation is not the case in some countries, including China, Norway, and Finland. Drivers in these countries may not follow the full compliance with the official priority rules and instead fail to yield [1–3]. Left-turning vehicles always attempt to choose the shortest path where the potential conflict point is nearer to themselves than through-vehicles. Once an opposing through-vehicle accommodates a left-turning vehicle's crossing, the following left-turning vehicles will take this opportunity to finish their turning movements. As a result, through-vehicles are undoubtedly severely delayed [4]. Thus, the opposed crossing flow will also strive to maintain a small time headway to prevent being disturbed by the conflicting traffic flow. It cannot be denied that maintaining such a small time headway calls for a driver's quick reaction; nevertheless, the nonstrict priority maneuver may improve the capacity of a left lane. In particular, when the opposing approach has a high through-flow, the nonstrict priority maneuver will result in more left turns crossing the intersection and mitigate the effect of left-turning spillover on through-vehicles in the same direction. This result explains also why traffic management officials in these countries acquiesce to the nonstrict priority behaviors of left-turning vehicles.

In addition, scholars and engineers who study autonomous vehicles should also focus on the nonstrict priority behaviors of left-turning vehicles, especially for mixed traffic flow with human-driving and autonomous vehicles. At an intersection with permitted left-turning phase, through autonomous vehicles must pay close attention to opposed left-turning vehicles by human-driving and then decide whether it can cross the intersection. According to the capacity model under nonstrict priority, the significant factors will be obtained as well. Then, it can provide reference on optimizing the coordination strategy of the autonomous vehicles, to improve the capacity of the intersection with a permitted left-turning phase.

Many scholars have conducted studies on intersection capacity under a permitted phase. Existing methods can be categorized into two aspects: traditional method for two traffic flows with strict priority and platoon method for two flows with the same priority.

1.1. Traditional Methods. The traditional methods used to compute the capacity of a permitted left-turn lane mostly follow a strict priority [5]. The procedure of the *Highway Capacity Manual* [6] uses eight adjustment factors to estimate the left-turn saturation flow rate. In addition, the operations of the permitted left-turning stream are divided into three periods: (1) before the first left-turning vehicle arrives; (2) left turns are obstructed by opposing through-flow; (3) left turns find the acceptable gaps and finish their turning movements after clearance of the opposing queue. Similarly, the *Canadian Capacity Guide for Signalized Intersection* [7] also utilizes the saturation adjustment factor that is relevant to the green splits and the weight of through- and left-turning flows. In contrast, the SIDRA model [8] and the Levinson method [9] adjust the capacity by reducing lost green times caused by lane blockages. The SIDRA model is a gap-acceptance-based model, and the iterative technique is used to determine the capacity. Levinson's model is not so complicated, and it assumes that the capacity is affected by blockages of left-turning vehicles in the same direction and the opposing direction. These models are classical models, but they are limited to left-turning vehicles under the assumption of full compliance with the right-of-way.

1.2. Platoon Method. The platoon method was first proposed by Wang [10] to calculate the capacity of an unsignalized intersection. His observation showed that drivers preferred to cross through the intersection alternately via a platoon of vehicles, especially during a peak hour. In fact, these studied intersections operate under a nonstrict priority. Meng et al. [11] performed an extended study of an unsignalized intersection with dual lanes. In his analysis, conflicts between left turns and oncoming flows were simplified to be those between two through-flows with large critical gap and follow-up times. Subsequently, Li and Song [12] improved the capacity model, taking into account the influence of nonmotorized vehicles and pedestrians. These works certainly improved the capacity under nonstrict priority. However, they oversimplified the intersection operation and neglected the characteristics of left-turning traffic streams. In addition, driver maneuvers during a permitted phase are different from those at an unsignalized intersection.

According to Bai's empirical study on permitted left-turning maneuvers, left-turning vehicles would release in the form of a left-turn group under nonstrict priority. In his study, a left-turn group is comprised of all the vehicles turning at the same time without interruption by through-vehicles (saturation flow) or all those turning without interruption and with a time headway of no more than four seconds (unsaturation flow), as shown in Figure 1. He proposed that once the leading left-turning vehicle obtains a gap, the following vehicles will strive to maintain a small interval and cross through the intersection. Moreover, the following drivers prefer to begin their turning movement before the vehicle ahead to preempt the potential conflict point with opposing through-vehicles. The left-turning vehicle will not stop and wait for another chance to cross the intersection until the time its wheel may touch the centerline if the vehicle continues its turning movement. The phenomenon also indicates that the number of vehicles a left-turn group can accommodate is related to the intersection geometry.

The objective of this study was to develop the capacity model of an exclusive left lane with a permitted phase under a nonstrict priority. A field survey was first conducted to explore the maximum number of vehicles in a left-turn group and the releasing process of permitted left turns. Next, methodologies for measuring exclusive left-lane capacity were proposed on the basis of survey results. The following section describes sensitivity analysis and a comparison analysis with the model under strict priority. The final section presents the conclusions.

2. Field Survey

To gain a better understanding of the permitted left-turn operations under a nonstrict priority, a field survey was conducted at 19 approaches from 8 intersections in the city of Changchun, China, during the months of April through September 2014. The survey was conducted during peak hour periods because a high left-turning flow rate is more likely to occur during those periods. Finally, a total of 648 cycles were observed.

Table 1 gives the basic information of each approach. Here, the extension distance, a new concept, is proposed to describe the intersection geometry. The extension distance is defined as the length between the stop line at an entering approach and the double yellow centerline markings at the exiting approach, as shown in Figure 2.

$$Gp_{\mathrm{L}} = \langle 4.5 \ln L_{\mathrm{ex}} - 6.8 \rangle. \quad (1)$$

Two significant results will be obtained from the field survey: the maximum number of vehicles in a left-turn group and the releasing process of permitted left turns. These survey results will offer the basis for measuring the capacity of an exclusive left lane with a permitted phase under nonstrict priority.

2.1. The Maximum Number of Vehicles in a Left-Turn Group. It is found that a left-turn group will accommodate more left-turning vehicles with the increase of the extension distance. The logarithmic model is found to provide a better fitting result, with an R^2 (0.85) higher than that of the linear model ($R^2 = 0.80$). Figure 3 shows the fitting line and original data points. The regression-based logarithmic model for predicting the maximum number of vehicles in a left-turn group is as follows:where L_{ex} is the extension distance (m) and Gp_{L} is the maximum number of vehicles in a left-turn group (pcu), and with the value rounded to the nearest integer.

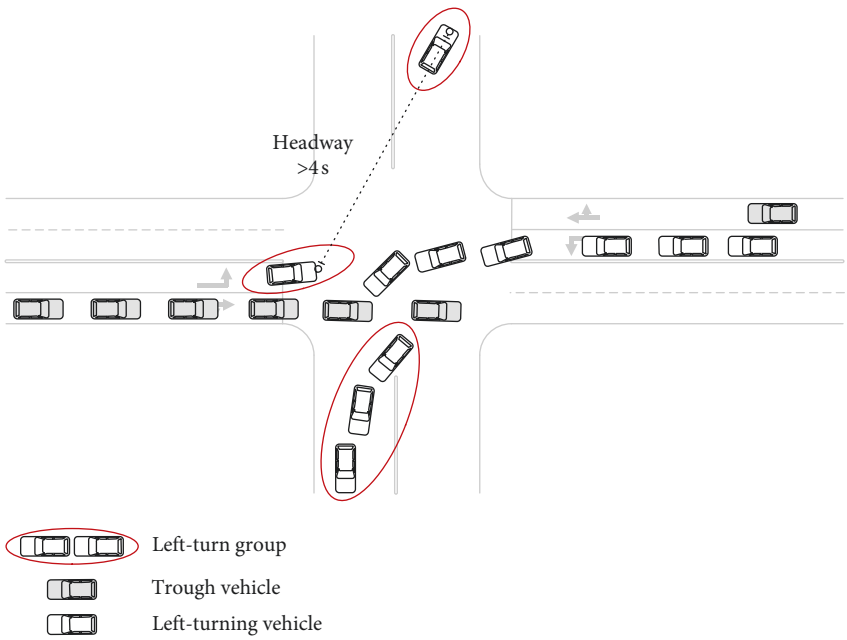

Figure 1: The definition of a left-turn group.

Table 1: Description of field sites.

Intersection	Approach	Cycle length (seconds)	Number of surveyed cycles	Extension distance (meters)	Maximum volume of a left-turn group (pcu)
Feiyue rd.-Dongfeng str.	E.	155	20	10	4
	W.	155	20	15	5
Heping rd.-Haoyue str.	N.	140	52	19	6
	S.	140	52	21	8
	W.	140	52	23	7
	E.	140	52	27	8
Jianshe str.-Bei'an rd.	E.	130	30	16	5
	W.	130	30	16	5
Tongzhi str.-Chaoyang rd.	W.	133	30	16	5
	E.	133	30	16	6
Tongzhi str.-Zhonghua rd.	W.	133	30	19	6
	E.	133	30	19	7
Tongzhi str.-Xi'an rd.	S.	175	20	36	9
Tongzhi str.-Ziyou rd.	N.	187	30	19	6
	S.	187	30	20	7
Zhuhai rd.-Huizhan str.	N.	105	35	15	5
	E.	105	35	17	6
	S.	105	35	17	6
	W.	105	35	20	7

The extension distance at these sites ranges from 10 m to 36 m. Because of the good-fit of the regression model, a length of 40 m was thought to be the maximum length for the application of equation (1). In addition, there is few signalized intersection with a permitted phase of an extension distance longer than 40 m.

2.2. Releasing Process of Permitted Left Turns. Under non-strict priority, permitted left-turning vehicles will cross the intersection in a left-turn group, which may lead to a severe delay for the opposed crossing flow. Thus, these vehicles will strive to maintain a small time headway to prevent being disturbed by the conflicting traffic flow, especially at peak hours. It is difficult for left-turning vehicles to find an acceptable gap in a continuous through-flow. Using the field survey, it was found that permitted left turns will release in two stages.

2.2.1. Stage 1. At the beginning of a circular green indication, no conflict traffic flows exist within the intersection. The first left-turning vehicle in the queue prefers a shorter path to cross the intersection to make the potential conflict point with opposed through-flows nearer to itself. This observation indicates that following vehicles in the left-

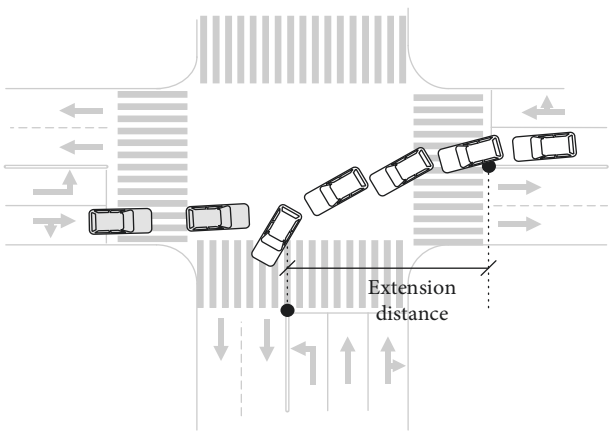

Figure 2: The definition of the extension distance.

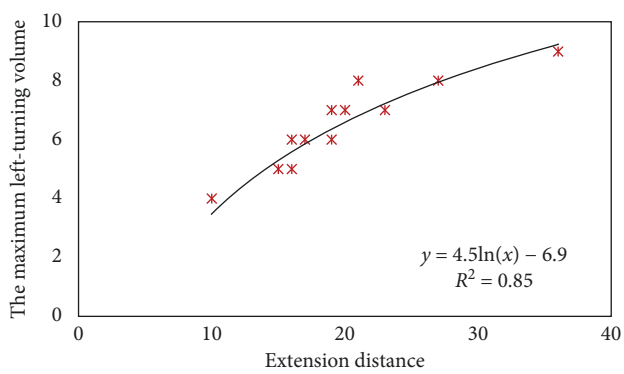

Figure 3: The maximum left-turning volume for various extension distances.

turn group will certainly cross the intersection. As a result, when opposing through-vehicles approach the intersection, they have to stop to accommodate the crossing maneuver of a left-turn group. According to the surveyed data, 81 percent of all 648 cycles exhibit the phenomenon that a left-turn group took precedence over vehicles at the beginning of the permitted phase, as shown in Figure 4(a).

2.2.2. Stage 2. Stage 2 begins after vehicles in the first left-group have finished their turning movements and lasts until the permitted phase ends. After the first left-turn group is released, the opposing through-vehicles will release in a continuous flow. These vehicles will strive to maintain a small time headway to prevent being disturbed by the conflict traffic flow, especially at peak hours. It is difficult for a left-turning vehicle to find an acceptable gap in a continuous through-flow. Once a right-turning vehicle exists, an acceptable gap will appear in the opposing through-stream and a left-turn group will take the opportunity to finish their turns. Thus, the opposing through-vehicles after these right turns have to accommodate their crossing and be severely delayed, as shown in Figure 5.

How an acceptable gap appears was carefully observed in the field survey. The result is shown in Figure 4(b). Under nonstrict priority, most of left-turn groups use the gap provided by opposing right turns. In addition, eighteen percent of left-turn groups found acceptable gaps in the unsaturated opposing through-flow. Others encounter either accidents or illegal pedestrian crossings that obstructed opposing through-vehicles.

3. Methodology

3.1. Computation of Stage 1. According to the aforementioned analysis, the left-turning capacity in stage 1 can be calculated as the maximum number of vehicles in a left-turn group, as shown in the following equation:

$$\mathrm{CAP}_1 = \frac{3600}{C} G p_{\mathrm{L}} = \frac{3600\langle 4.5 \ln L_{\mathrm{ex}} - 6.8\rangle}{C}, \tag{2}$$

where CAP_1 is the capacity in stage 1 (pcu/h) and C is the signal cycle length in seconds.

3.2. Computation of Stage 2. Assuming that t_{L} is the time headway of a left-turning vehicle in a left-turn group and g is the green time of the permitted phase, the duration time of stage 2 will be $g - t_{\mathrm{L}} \times G p_{\mathrm{L}}$. Platoons in two directions are assumed to be infinite because the maximum released volume is expected. The following five steps are used to calculate the left-turning capacity during stage 2.

3.2.1. Step 1 the Probability of m Opposed Right-Turning Vehicles' Arrivals. In stage 2, the left-turning capacity is closely related to the number of opposing right turns. The arrival characteristics of right-turning vehicles should be first determined. There will be one left-turn group crossing the intersection as long as the opposing right-turning vehicle appears, regardless of how many of these right-turning vehicles are present.

At an entering approach, traffic flows are crowdedand and lane-change behavior is rare. Thus, the binomial distribution is selected to describe the arrival characteristics of right-turning vehicles, as shown in the following equation:

$$P(N_{\mathrm{R}} = m) = C_{N_{\mathrm{T+R}}}^{m} p_{\mathrm{R}}^{m} (1 - p_{\mathrm{R}})^{N_{\mathrm{T+R}} - m}, \tag{3}$$

where $P(N_{\mathrm{R}} = m)$ is the probability of m right-turning vehicles' arrivals when there are $N_{\mathrm{T+R}}$ vehicles (both through and right turn) arriving at the opposed approach with the rate of right-turning vehicles p_{R} during $G p_{\mathrm{l}} \times t_{\mathrm{L}}$ seconds.

3.2.2. Step 2 the Expectation of the Gap Number Provided by Right Turns. According to the aforementioned logic, each acceptable gap produced by right-turning vehicles could accommodate a left-turn group. In this step, the expectation of the gap number $E_{N_{\mathrm{R}}=m}$ is considered.

Case 1 ($m = 0$). No right-turning vehicles are arriving and left-turning vehicles cannot cross the intersection during the period. Thus, the expectation of the gap number $E_{N_{\mathrm{R}}=m}$ under this case is zero.

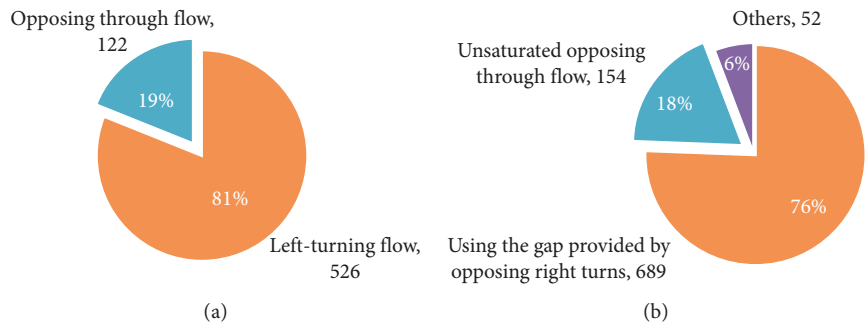

Figure 4: Field surveyed results. (a) The flow crossing the intersection when the permitted phase start. (b) The reason why an acceptable gap for left-turn appears.

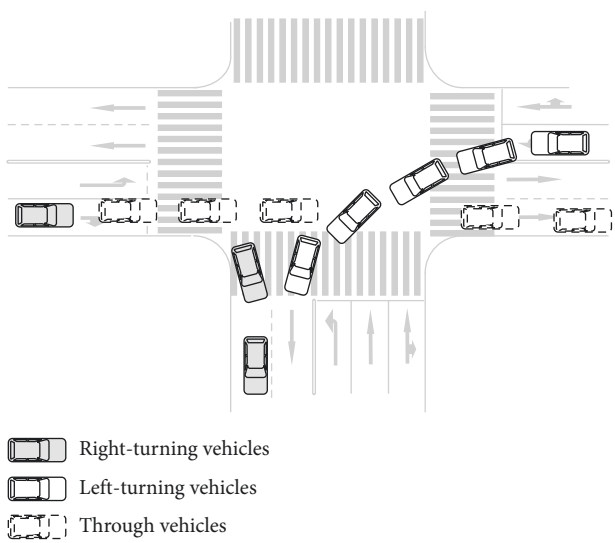

Figure 5: Opposing right turns provide opportunities for the crossing of left-turning vehicles.

Case 2 ($m = N_{T+R}$). All the arriving vehicles are right-turning. The period selected is duration of a releasing time of all the left-turning vehicles in a left-turn group, and there will still be only one left-turn group that can finish turning movements. Thus, $E_{N_R=m} = 1$.

Case 3 ($0 < m < (1/2)N_{T+R}$). In this case, the number of right-turning vehicles is less than that of the crossing-through vehicles. These m right-turning vehicles can be divided into at least one part and no more than m parts. Different parts of the right-turning vehicles should be placed into different gaps in cross-through flow. A portion of the right-turning vehicles can be placed after the last cross-through vehicle but cannot be placed before the first one. Here, the combination number should be used, and $C^x_{N_{T+R}-m}$ possibilities can be obtained when m right-turning vehicles are divided into x parts. The expectation of the gap number can be calculated using the following equation:

$$E_{N_R=m} = \frac{\left(1 \times C^1_{N_{T+R}-m} + 2 \times C^2_{N_{T+R}-m} + \cdots + m \times C^m_{N_{T+R}-m}\right)}{C^1_{N_{T+R}-m} + C^2_{N_{T+R}-m} + \cdots + C^m_{N_{T+R}-m}}. \tag{4}$$

Case 4 ($(1/2)N_{T+R} \le m < N_{T+R}$). In this case, the number of right-turning vehicles is more than that of the crossing-through vehicles. In addition, the cross-through flow has no more than $N_{T+R} - m$ gaps. Thus, m right-turning vehicles can be divided into at least one part and no more than $N_{T+R} - m$ parts. The expectation of the gap number can be calculated using the following equation:

$$E_{N_R=m} = \frac{\left(1 \times C^1_{N_{T+R}-m} + 2 \times C^2_{N_{T+R}-m} + \cdots + (N_{T+R} - m) \times C^{N_{T+R}-m}_{N_{T+R}-m}\right)}{C^1_{N_{T+R}-m} + C^2_{N_{T+R}-m} + \cdots + C^{N_{T+R}-m}_{N_{T+R}-m}}. \tag{5}$$

The expectation of the gap number can be calculated using the following equation:

$$E_{N_R=m} = \frac{\sum_{i=1}^{N_{T+R}-m} i C^i_{N_{T+R}-m}}{\sum_{i=1}^{N_{T+R}-m} C^i_{N_{T+R}-m}}. \tag{6}$$

3.2.3. Step 3 Releasing Time for All Arrivals. In this step, equation (7) is proposed to determine how long it will take to release all arriving vehicles containing $E_{N_R=m} \times Gp_L$ permitted left-turning vehicles and $N_{T+R} - m$ cross-through vehicles:

$$T_{\text{release}-m} = E_{N_R=m} \times Gp_L \times t_L + (N_{T+R} - m) \times t_T, \tag{7}$$

where $T_{\text{release}-m}$ is time required to release all arrived vehicles (second), t_L is the time headway of the left-turning vehicles (second), and t_T is the time headway of the through-vehicles (second).

3.2.4. Step 4 Releasing Capacity during Stage 2 with m Opposed Right-Turning Vehicles. On the condition that there are N_{T+R} opposing traffic arrivals with m right turns, equation (8) gives the mathematical expectation of the released left-turning volume in a single traffic control cycle:

$$\mathrm{CAP}_{\mathrm{L},N_{\mathrm{R}}=m} = E_{N_{\mathrm{R}}=m} \times Gp_{\mathrm{L}} \frac{g - t_{\mathrm{L}} \times Gp_{\mathrm{L}}}{E_{N_{\mathrm{R}}=m} \times Gp_{\mathrm{L}} \times t_{\mathrm{L}} + (N_{\mathrm{T+R}} - m) \times t_{\mathrm{T}}}. \tag{8}$$

3.2.5. Step 5 Releasing Capacity during Stage 2. For equation (8), m can take values from 0 to $N_{\mathrm{T+R}}$, and each $\mathrm{CAP}_{\mathrm{L},N_{\mathrm{R}}=m}$ has a probability of $P(N_{\mathrm{R}} = m)$. Thus, the releasing capacity during stage 2 can be estimated by equation (9), assuming C is the signal control cycle of the intersection:

$$\begin{aligned}\mathrm{CAP}_2 = {} & P(N_{\mathrm{R}} = 0) \times E_{N_{\mathrm{R}}=0} \\ & \times Gp_{\mathrm{L}} \frac{g - t_{\mathrm{L}} \times Gp_{\mathrm{L}}}{E_{N_{\mathrm{R}}=0} \times Gp_{\mathrm{L}} \times t_{\mathrm{L}} + (N_{\mathrm{T+R}} - 0) \times t_{\mathrm{T}}} \\ & \times \frac{3600}{C} + P(N_{\mathrm{R}} = 1) \times E_{N_{\mathrm{R}}=1} \\ & \times Gp_{\mathrm{L}} \frac{g - t_{\mathrm{L}} \times Gp_{\mathrm{L}}}{E_{N_{\mathrm{R}}=1} \times Gp_{\mathrm{L}} \times t_{\mathrm{L}} + (N_{\mathrm{T+R}} - 1) \times t_{\mathrm{T}}} \\ & \times \frac{3600}{C} + \cdots + P(N_{\mathrm{R}} = m) \times E_{N_{\mathrm{R}}=m} \\ & \times Gp_{\mathrm{L}} \frac{g - t_{\mathrm{L}} \times Gp_{\mathrm{L}}}{E_{N_{\mathrm{R}}=m} \times Gp_{\mathrm{L}} \times t_{\mathrm{L}} + (N_{\mathrm{T+R}} - m) \times t_{\mathrm{T}}} \\ & \times \frac{3600}{C} + \cdots + P(N_{\mathrm{R}} = N_{\mathrm{T+R}}) \times E_{N_{\mathrm{R}}=N_{\mathrm{T+R}}} \\ & \times Gp_{\mathrm{L}} \frac{g - t_{\mathrm{L}} \times Gp_{\mathrm{L}}}{E_{N_{\mathrm{R}}=N_{\mathrm{T+R}}} \times Gp_{\mathrm{L}} \times t_{\mathrm{L}} + (N_{\mathrm{T+R}} - N_{\mathrm{T+R}}) \times t_{\mathrm{T}}} \\ & \times \frac{3600}{C}.\end{aligned} \tag{9}$$

Equation (9) can be simplified to

$$\mathrm{CAP}_2 = \frac{3600}{C} (g - t_{\mathrm{L}} \times Gp_{\mathrm{L}}) Gp_{\mathrm{L}} \cdot \sum_{j=0}^{N_{\mathrm{T+R}}} \frac{P(N_{\mathrm{R}} = j) \times E_{N_{\mathrm{R}}=j}}{E_{N_{\mathrm{R}}=j} \times Gp_{\mathrm{L}} \times t_{\mathrm{L}} + (N_{\mathrm{T+R}} - j) \times t_{\mathrm{T}}}. \tag{10}$$

The left-turning capacity is the sum of CAP_1 and CAP_2, as shown in the following equation:

$$\begin{aligned}\mathrm{CAP} &= \mathrm{CAP}_1 + \mathrm{CAP}_2 \\ &= \frac{3600}{C} \left[Gp_{\mathrm{L}} + (g - t_{\mathrm{L}} \times Gp_{\mathrm{L}}) Gp_{\mathrm{L}} \cdot \sum_{j=0}^{N_{\mathrm{T+R}}} \frac{P(N_{\mathrm{R}} = j) \times E_{N_{\mathrm{R}}=j}}{E_{N_{\mathrm{R}}=j} \times Gp_{\mathrm{L}} \times t_{\mathrm{L}} + (N_{\mathrm{T+R}} - j) \times t_{\mathrm{T}}} \right].\end{aligned} \tag{11}$$

4. Discussion

4.1. Validation. Regression analyses were conducted in this study to measure the accuracy of the proposed capacity model. In fact, it is difficult to obtain the actual capacity from a field survey because saturation flow will not last for the whole surveyed period. In addition, if left-turning vehicles always release in saturation flow, a protected phase should be considered at the intersection. In this study, the number of crossing left turns in three adjacent cycles is selected to convert into the observed maximum volumes in an hour. Scatter plots and regression lines for the proposed capacity are shown in Figure 6.

In the figure, the linear form is used to validate the capacity model. If the predicted value is equal to observed value, the regression line for scatter plots will be $y = x$. The coefficient of determination R^2 for the regression line under nonstrict priority is 0.86, indicating that predicted and observed values have strong linear relationship. And, the regression line has a slope of 0.95, which is quite close to the ideal line. The intercept of the regression line is 49.23, implying that the predicted value is close to but slightly higher than the observed value. However, the regression line under strict priority is quite different from the ideal line, with 0.41 as slope and 132.97 as intercept. And, its R^2 (0.35) shows that linear relationship between predicted and observed values is very weak. Thus, the method proposed can obtain better result than the method under strict priority.

Because of some unsaturated flows in the surveyed cycles, it is reasonable that an exclusive left lane cannot reach its capacity in reality. However, the predicted values from the method under strict priority are quite different from the surveyed values. Most of them are smaller than the observed maximum volume. This result indicates that an exclusive left lane can release more vehicles under nonstrict priority than that under strict priority.

4.2. Sensitivity Analysis. There are eight parameters in the proposed capacity model. All these factors will have an impact on the left-lane capacity. Figure 7 shows the relationships among the time headway of left turns t_{L}, the time headway of crossing through t_{T}, and the left-lane capacity, while other parameters, such as C, g, Gp_{L}, p_{R}, and $N_{\mathrm{T+R}}$, remain the same. It can be seen from the figure that t_{L} has a greater impact on the capacity compared to t_{T}. The left-lane capacity will have a sharp decrease when t_{L} increases, especially with a large t_{T} value. However, these seven curves will have little difference when the value of t_{L} is large.

Figure 8 shows the relationships among the opposed through and right-turning arriving volume $N_{\mathrm{T+R}}$, the rate of right turns p_{R}, and the left-lane capacity, while other parameters, such as C, Gp_{L}, g, t_{L}, and t_{T}, remain the same. It is clear that p_{R} is more sensitive to the capacity. In the case of $p_{\mathrm{R}} = 0$, there are no right turns. Left-turning vehicles can only cross the intersection during stage 1. In contrast, left-turning flows can continuously cross the intersection during the whole permitted phase if the arriving vehicles are all right turns ($p_{\mathrm{R}} = 1$). In addition, the capacity-lane capacity will only depend on C, Gp_{L}, g, and t_{L}. Thus,

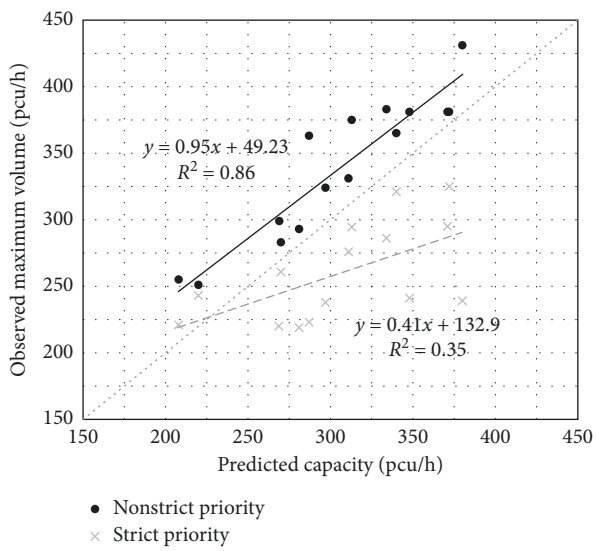

Figure 6: Capacity model validation.

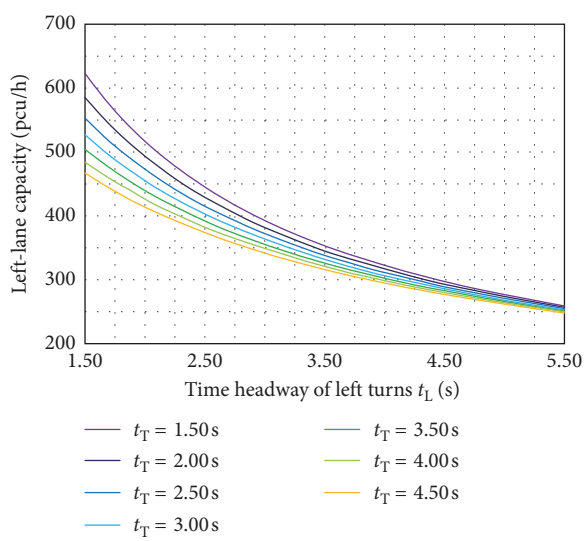

Figure 7: Sensitivity of left-lane capacity to time headway of left turns and crossing through.

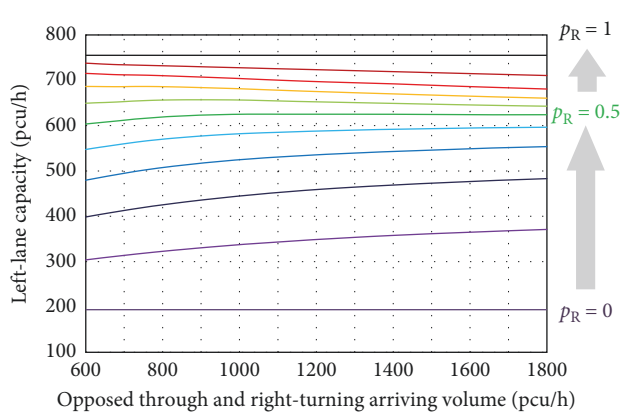

Figure 8: Sensitivity of left-lane capacity to opposed arriving volume and the rate of right turns p_R.

capacities with $p_R = 0$ and $p_R = 1$ are both constant. When p_R is less than 0.5, the left-lane capacity will increase with increasing arriving volume. More right-turning vehicles will provide more opportunities for crossing of the left-turning vehicles. However, when the rate of right turns is higher than 0.5, a large arriving volume will reduce the left-lane capacity because more through-vehicles will occupy the permitted phase and reduce the time for left-turning vehicles.

5. Conclusion

The work conducted in this paper is a continuation of the authors' previous studies regarding nonstrict priority left-turning maneuvers to determine the capacity of an exclusive left-lane with a permitted phase. A new method to estimate the capacity was developed on the basis of the following observation results from field surveys at 19 sites:

(1) There are a maximum number of vehicles in a left-turn group that is related to the extension distance of an intersection

(2) Permitted left-turning vehicles always have non-yielding maneuvers and cross the intersection before through-vehicles when a green phase starts

(3) Left-turn groups will use gaps provided by opposing right-turns to finish their turning movements and severely delay through-vehicles, especially during peak hours

The methodology contained two stages: the first left-turn group crossing at the beginning of a permitted phase (stage 1) and the following left-turn groups crossing using gaps provided by opposing right-turns (stage 2). Probability theory and regression models were used in the computational process. In the model discussion, the time headway of the left-turning vehicles and the rate of opposing right-turning vehicles were proved to be more sensitive to the left-lane capacity. Next, left-turn capacities estimated by the proposed model were compared to the capacity from strict priority and observed maximum left-turning volumes. The results showed the model was valid to estimate the capacity of an exclusive left lane with a permitted phase under nonstrict priority.

Data Availability

The data of this research article are available from the first author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] W. Brilon and T. Miltner, "Capacity at intersections without traffic signals," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1920, no. 1, pp. 32–40, 2005.

[2] S. Li, D. Qian, and N. Li, "BP simulation model and sensitivity analysis of right-turn vehicles' crossing decisions at signalized intersection," *Journal of Transportation Systems Engineering and Information Technology*, vol. 10, no. 2, pp. 49–56, 2010.

[3] D. Lin, W. Ma, L. Li, and Y. Wang, "A driving force model for non-strict priority crossing behaviors of right-turn drivers," *Transportation Research Part B: Methodological*, vol. 83, pp. 230–244, 2016.

[4] Q. W. Bai, Y. H. Chen, Z. W. Qu, P. F. Tao, N. B. Cao, and Y. Shen, "Nonstrict priority left-turning maneuvers with a permitted phase at signalized intersections: empirical study in China.," *Journal of Transportation Engineering, Part A: Systems*, vol. 143, no. 3, article 04016009, 2017.

[5] H. S. Levinson and E. S. Prassas, "Capacity of shared left turn lanes-comparative analysis," *Journal of Transportation Engineering*, vol. 127, no. 2, pp. 132–142, 2001.

[6] Transportation Research Board, *Highway Capacity Manual*, National Research Council, Washington, DC, USA, 2010.

[7] S. Teply, D. I. Allingham, D. B. Richardson, and B. W. Stephenson, *Canadian Capacity Guide to Signalized Intersections*, Institute of Transportation Engineers, Toronto, Canada, 2012.

[8] R. Akcelik, "Opposed turns at signalized intersections—the Australian method," *ITE Journal*, vol. 59, no. 6, pp. 21–27, 1989.

[9] H. S. Levinson, "The capacity of shared left turn lanes-a simplified approach," *Journal of the Transportation Research Board*, vol. 1989, no. 1225, pp. 45–52, 1989.

[10] W. Wang, "Platoon method of analyzing capacity and delay of non-signalized intersection," *Journal of Highway and Transportation Research and Development*, vol. 1989, no. 3, pp. 70–79, 1989.

[11] Y. P. Meng, W. Deng, and L. Ge, "Analysis for two-roadway uncontrolled intersection of capacity by motorcade analysis method," *Journal of Highway and Transportation Research and Development*, vol. 22, no. 12, pp. 119–122, 2005.

[12] A. Z. Li and X. H. Song, "Capacity calculation method of urban road all-way stop-controlled intersections," *Journal of Transportation Systems Engineering and Information Technology*, vol. 14, no. 1, pp. 200–208, 2014.