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Preliminary communication

# Study on the Applicable Conditions for Protective Left-Turn Phase and Permissive Left-Turn Phase

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**Abstract:** In order to improve the operation efficiency of intersections and make traffic management more scientific, this paper conducts a research on the application conditions for protective left-turn phase and permissive left-turn phase. Taking the traffic efficiency model as a constraint and VISSIM simulation as research means, this paper makes a comparative analysis of the traffic efficiency under different flow conditions using different control means, so as to obtain the specific traffic flow conditions applicable to different control means. This research aims to provide data support for the scientific application of traffic management.

**Keywords:** permissive left-turn; protective left-turn; signal control; traffic efficiency; traffic engineering

## 1 INTRODUCTION

The most serious conflict at intersections arises from left turning and straight going [1]. Researchers have always paid high attention to left turning. Currently, although high priority is given to left-turning traffic flow, there is less discussion on the selection of phase. For a standard four-way intersection, the discussion on the protective left-turn phase and the permissive left-turn phase comes down to the selection of two-phase or four-phase. The four-phase selection is more extensive, including not only the protective left-turn phase, but also the unilateral rotation at the four-way intersection [2].

Congestion can be effectively alleviated by using reasonable control methods at intersections. In 2014, Shen and Wang [3] provided the selection criteria from the perspective of traffic flow. In 2016, Shen and Wang [4] also discussed the selection of two-phase and four-phase from the perspective of intersection operation efficiency. In 2017, Schattler et al. [5] discussed the safety issues of combining yellow arrow light with different left-turning controls. In 2019, Li et al. [6] evaluated the protective left-turn phase and the permissive left-turn phase from the perspective of safety, and evaluated the delay of the two phases. In 2020, Adamson et al. [7] discussed the boundary between protective and permissive left-turn with a safety evaluation model. At the same time, the discussion about left-turn mainly focuses on how to calculate the interval time of left-turn when different methods are adopted [8]. In 2021, Zhang et al. [9] evaluated the severity of driver injury in traffic accidents caused by different left-turn controls, and the innovation of left-turn methods. For example, many new left-turn methods gradually emerge, such as the setting of left-turn waiting area [10], the realization conditions for contraflow left-turn [11, 12]. This paper tries to find the standard for phase setting from the perspective of layout and flow, and change the current trial selection of phase at intersections.

Although the protective left-turn phase and permissive left-turn phase are ancient forms of control, they are widely used. It takes time for the travelers to adapt to contraflow left-turn, therefore it is essential to refine the existing control form.

## 2 LIMITATIONS OF THE PLANE LAYOUT OF PROTECTIVE LEFT-TURN PHASE AND PERMISSIVE LEFT-TURN PHASE

In terms of left-turn and through traffic flow at intersections, when the two share the same lane, the protective left-turn phase cannot be used, but when a left-turn lane is set alone, both the protective left-turn phase and the permissive left-turn phase can be applied (as shown in Fig. 1 and Fig. 2). The safety of the permissive left-turn phase is inferior to that of the protective left-turn phase [13], so it should be used with caution in traffic control. In this case, the conflict between through going and left turning is mainly considered, which mainly depends on the traffic flow [14].

**Figure 1** Setting of lane for through-going and left-turning merging

**Figure 2** Setting of lanes for left-turning only

In order to comprehensively consider the performance of roads in terms of service level and utilization of road capacity, the original intention of section traffic efficiency is to determine the critical traffic volume of road facility service level. Considering the urban road intersection and what we are looking for is the restriction of traffic volume, this study adopts the section traffic efficiency as the evaluation index to evaluate the urban management capacity [15, 16]. Werner Brilon believes that [17] in unit time, the more vehicles run at a faster speed, the higher the traffic efficiency is [18]. Through the above analysis, the traffic flow efficiency can be expressed as:

$$E = Q \cdot v \tag{1}$$

where: $E$ - efficiency of traffic flow, pcu·km/h; $Q$ - the amount of traffic flow per unit time, pcu; $v$ - the average speed of traffic flow, km/h.

In order to compare the traffic efficiency of intersections under the two-phase and four-phase control mode at the same time, two parameters of green light display time and cycle length are introduced, so as to obtain the two-phase and four-phase traffic efficiency model.

## 3 TRAFFIC EFFICIENCY MODEL

The traffic efficiency model is improved to make it more suitable for urban road traffic control. In a two-phase signalized intersection, if the straight traffic flow in this direction and the left turning traffic flow in the opposite direction are released at the same time in a cycle, the traffic efficiency of the two-phase intersection is [17, 19]:

$$E_1 = \frac{g_i \left( Q_{\text{Straight}} v_{\text{Straight}} + g_{i2} \cdot Q_{\text{Left-turn}} v_{\text{Left-turn}} \right)}{C} \tag{2}$$

where: $g_i$ - release time of two traffic flows in a cycle, s; $C$ - length of signal cycle, s; $Q_{\text{Straight}}$, $Q_{\text{Left-turn}}$ - straight traffic flow and left-turn traffic flow through the intersection in unit time, pcu; $v_{\text{Straight}}$, $v_{\text{Left-turn}}$ - average speed of straight traffic flow and left-turn traffic flow through the intersection, km/h.

In a four-phase signalized intersection, within a cycle, the straight traffic flow in this direction is separated from the left turning traffic flow in the opposite direction. The timespan of the green light for the release of the straight traffic flow is set as $g_{i1}$, that for the left turn traffic flow is set as $g_{i2}$, and the cycle length is set as $C$, then the release time is g/C. The traffic efficiency of two-phase intersection is:

$$E_2 = \frac{\left( g_{i1} \cdot Q_{\text{Straight}} v_{\text{Straight}} + g_{i2} \cdot Q_{\text{Left-turn}} v_{\text{Left-turn}} \right)}{C} \tag{3}$$

where: $g_{i1}, g_{i2}$ - release time of straight traffic flow and left-turning traffic flow in a cycle, s; $C$ - length of signal cycle, s; $Q_{\text{Straight}}$, $Q_{\text{Left-turn}}$-straight traffic flow and left-turn traffic flow through the intersection in unit time, pcu; $v_{\text{Straight}}$, $v_{\text{Left-turn}}$ - average speed of straight traffic flow and left-turn traffic flow through the intersection, km/h.

## 4 TRAFFIC VOLUME CONDITIONS APPLICABLE TO PROTECTIVE LEFT-TURN PHASE AND PERMISSIVE LEFT-TURN PHASE

To ensure the universality of the results, the "cross" intersection is used in the simulation of this study. The road width 3.5 m is set as the standard road width [20], and the design speed on this section of road is 40 km/h. For lane selection, considering the fact that there are many through lanes in China, this study adopts three forms: a. one through lane and one left-turn lane; b. two through lanes and one left-turn lane; c. three through lanes and one left-turn lane. The number of straight vehicles and the number of left-turn vehicles increase by 100 pcu/h in turn. The timing method adopts mature and habitual Webster's method [21-23]. The signal control mode adopts three phases, and the phase organization scheme is shown in Fig. 3. The traffic efficiency of the east-west direction traffic volume is regarded as the traffic efficiency of the permissive left-turn, and the traffic efficiency of the north-south direction traffic volume is regarded as the traffic efficiency of the protective left-turn.

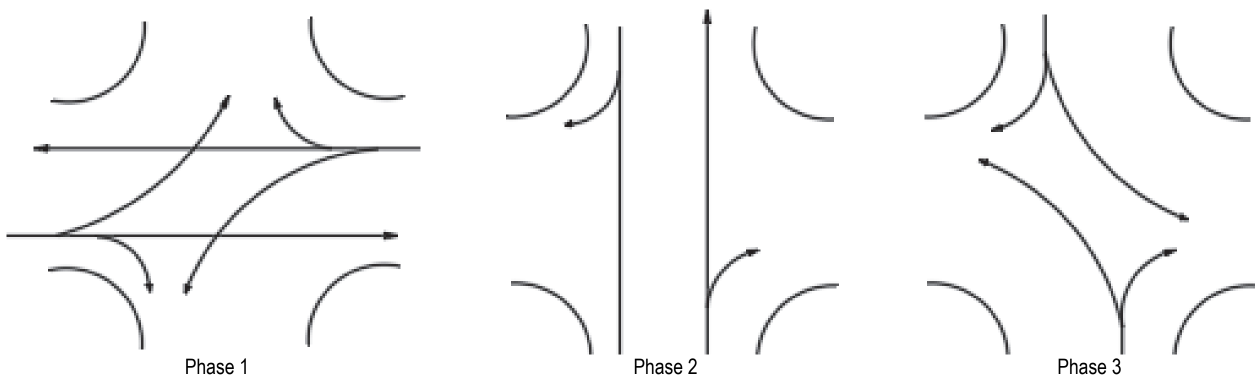


**Figure 3** Three phase diagram of cross intersection

### 4.1 One through Lane and One Left-Turn Lane

The timing for different traffic volume at the intersection is carried out in turn. When the traffic volume increases to a certain value and does not meet the timing requirements, the increase in traffic volume will be stopped. Tab. 1 is obtained through calculation.

Then the flow ratio of straight and left-turn traffic at each inlet is calculated to provide data support for subsequent signal timing.

The average speed is obtained by dividing the distance from the entrance lane to the exit lane with the time of vehicles passing through the intersection during the green light timespan. In the simulation model, the straight distance from the entrance lane to the exit lane is 40m, and the distance from the entrance lane to the exit lane is 30m if left-turning is chosen. When the green light is on, the time when the first vehicle in the queue passes the intersection and the time when the last vehicle passes the intersection are recorded respectively, and the average value is taken as the travel time [24, 25].

Through Vissim simulation [26] calculation, the Critical traffic volume of two-phase and four phase signal control mode conversion can be obtained. In order to facilitate the statistics, the total traffic volume in the straight direction is set as $Q_T$, the left turn traffic volume is recorded as $Q_L$. When $Q_T$ and $Q_L$ are in the feasible domain $A = A_1 \cup A_2 \cup A_3$, in order to improve the traffic efficiency of the intersection, the through traffic volume and the left turning traffic volume are released at the same time.

$$A_1 = \{Q_T \le 100\} \cap \{Q_L < 300\}$$
$$A_2 = \{100 < Q_T \le 300\} \cap \{Q_L < 200\}$$
$$A_3 = \{300 < Q_T \le 500\} \cap \{Q_L < 100\}$$

That is, when $Q_T$ and $Q_L$ are in the feasibility domain at the same time, the permissive left-turn signal control mode is adopted; when $Q_T$ and $Q_L$ do not meet the feasibility region standard, the protective left-turn signal control mode is adopted.

**Table 1** Signal timing table

| Through traffic volume: 100 pcu/h | | | | | |
|---|---|---|---|---|---|
| Left-turn traffic volume / pcu/h | Timespan of green light / s | | | Effective timespan of green light | Cycle / s |
| 100 | 9 | 8 | 8 | 25 | 40 |
| 200 | 12 | 6 | 12 | 30 | 45 |
| 300 | 19 | 7 | 19 | 45 | 60 |
| 400 | 33 | 9 | 33 | 75 | 90 |
| 500 | 70 | 15 | 70 | 155 | 170 |
| Through traffic volume 200 pcu/h | | | | | |
| Left-turn traffic volume / pcu/h | Timespan of green light / s | | | Effective timespan of green light | Cycle / s |
| 100 | 12 | 12 | 6 | 30 | 45 |
| 200 | 14 | 13 | 13 | 40 | 55 |
| 300 | 22 | 16 | 22 | 60 | 75 |
| 400 | 32 | 16 | 32 | 80 | 95 |
| Through traffic volume 300 pcu/h | | | | | |
| Left-turn traffic volume / pcu/h | Timespan of green light / s | | | Effective timespan of green light | Cycle / s |
| 100 | 19 | 19 | 7 | 45 | 60 |
| 200 | 22 | 22 | 11 | 55 | 70 |
| 300 | 25 | 25 | 25 | 75 | 90 |
| 400 | 58 | 44 | 58 | 160 | 175 |
| Through traffic volume 400 pcu/h | | | | | |
| Left-turn traffic volume / pcu/h | Timespan of green light / s | | | Effective timespan of green light | Cycle / s |
| 100 | 33 | 33 | 9 | 75 | 90 |
| 200 | 42 | 42 | 21 | 105 | 120 |
| 300 | 58 | 58 | 44 | 160 | 175 |
| Through traffic volume 500 pcu/h | | | | | |
| Left-turn traffic volume / pcu/h | Timespan of green light / s | | | Effective timespan of green light | Cycle / s |
| 100 | 70 | 70 | 15 | 155 | 170 |

### 4.2 Two through Lanes and One Left-Turn Lane

In this simulation, the calculation process of signal timing, average speed and traffic efficiency is the same as the above process. The intersection Vissim simulation model is as follows.

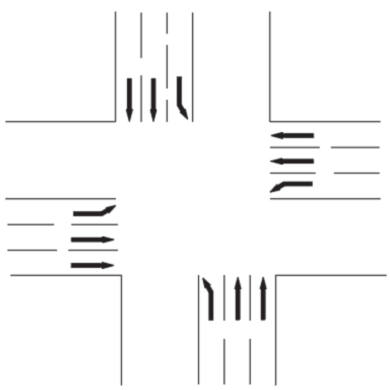

**Figure 4** Vissim simulation model of two straight lanes

Critical traffic volume of signal control mode conversion between permissive left-turn and protective left-turn phase. The traffic volume in the straight direction is set as $Q_T$, the left turn traffic volume is recorded as $Q_L$. When $Q_T$ and $Q_L$ are in the feasible domain $A = A_1 \cup A_2 \cup A_3 \cup A_4$, in order to improve the traffic efficiency of the intersection, the through traffic volume and the left turning traffic volume are released at the same time.

$$A_1 = \{Q_T \le 200\} \cap \{Q_L < 400\}$$
$$A_2 = \{200 < Q_T \le 300\} \cap \{Q_L < 300\}$$
$$A_3 = \{300 < Q_T \le 500\} \cap \{Q_L < 200\}$$
$$A_4 = \{500 < Q_T \le 700\} \cap \{Q_L < 100\}$$

That is, when $Q_T$ and $Q_L$ both are within the feasible domain, the permissive left-turn signal control mode is adopted; when $Q_T$ and $Q_L$ are not in the feasible domain, the protective left-turn signal control mode is adopted.

### 4.3 Three through Lanes and One Left-Turn Lane

In this simulation, the calculation process of signal timing, average speed and traffic efficiency is the same as the above process. The intersection Vissim simulation model is as follows.

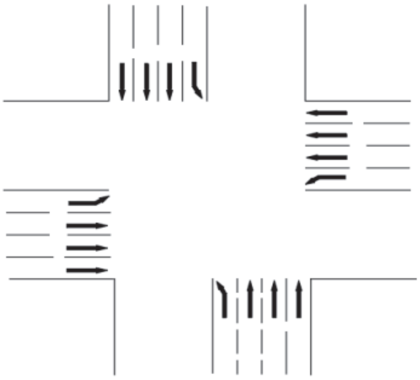

**Figure 5** Vissim simulation model of three straight lanes

Critical traffic volume of signal control mode conversion between permissive left-turn and protective left-turn phase. The traffic volume per hour in the straight direction is set as $Q_T$, the left turn traffic volume is recorded as $Q_L$. When $Q_T$ and $Q_L$ are in the feasible domain $A = A_1 \cup A_2 \cup A_3 \cup A_4 \cup A_5$ , in order to improve the traffic efficiency of the intersection, the through traffic volume and the left turning traffic volume are released at the same time.

$$A_1 = \{Q_T \le 500\} \cap \{Q_L < 500\}$$
$$A_2 = \{500 < Q_T \le 700\} \cap \{Q_L < 400\}$$
$$A_3 = \{700 < Q_T \le 1100\} \cap \{Q_L < 300\}$$
$$A_4 = \{1100 < Q_T \le 1300\} \cap \{Q_L < 200\}$$
$$A_5 = \{1300 < Q_T \le 1500\} \cap \{Q_L < 100\}$$

That is, when $Q_T$ and $Q_L$ both are within the feasible domain, the permissive left-turn signal control mode is adopted; when $Q_T$ and $Q_L$ are not in the feasible domain, the protective left-turn signal control mode is adopted.

## 5 CONCLUSION

The ultimate purpose of traffic signal control is to improve the operation efficiency of intersections, and the choice of different control forms is determined by the volume. Taking the traffic efficiency as the comparison standard to obtain the critical values of the two methods, it can be seen from the above analysis that the traversable gap for the through traffic volume on one lane decreases with the increase of traffic volume, and the two phases are applicable only when the left-turning volume is decreased. The four phases are more suitable for the situation where the left turn traffic volume and through traffic volume are relatively large. With the increase of the number of straight lines, the traversable gap barely shows up, so the two phases are applicable only when the volume on the through lane is decreased. When the left turn traffic flow is greater than 400 pcu/h/ln and the through traffic flow is greater than 500 pcu/h/ln, only four phases can be used. Considering the fact that there are many through lanes at most intersections and the number of left turn lanes is far less than that of through lanes, this paper adopts three lane distributions in the examples. The possibility of one lane of through traffic flow producing a crossing gap is not a simple double relationship with the possibility of two lanes producing a crossing gap, but the actual situation is more complex, and further in-depth analysis needs to be conducted for the situation when there are two or more left-turn traffic lanes.

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