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СОДЕРЖАНИЕ

ANALYSIS ON CALCULATION METHOD FOR SIGNALIZED INTERSECTION CAPACITY

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Abstract: To provide a scientific method for assessing the capacity of signalled intersections at different stages such as planning, design, and operation, this paper analyses a large-scale study on signalled intersection capacity from various countries, focusing on summarizing previous achievements in assessing the capacity of signalled intersections. "Saturation flow rate and effective green signal ratio are two key parameters for assessing traffic capacity: analyses were conducted on saturated flow rate, covering its various model forms, measurement methods, basic saturation flow rate and various correction parameter determination methods; The influencing factors, calculation methods and green signal ratio models for determining the effective green signal ratio were developed, timed and run for two main signal control modes. Finally, the research needs and the changing conditions of signal-controlled intersection capacity, as well as the specific issues that need to be addressed in this research area in cities, were discussed, and the development direction of signal-controlled intersection capacity research was discussed. The results show that current studies on the capacity of signalized intersections do not consider upstream and downstream conditions. Future research should focus on capacity calculation, uncertainty analysis in complex transport environments, and evaluating the efficiency of signalized intersections under high saturation conditions.

Keywords: methods, intersection capacity, signaled intersection, signalized intersection capacity, saturation flow rate, effective green time.

АНАЛИЗ МЕТОДА РАСЧЕТА ПРОПУСКНОЙ СПОСОБНОСТИ СИГНАЛИЗИРОВАННОГО ПЕРЕКРЕСТКА

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Аннотация: Чтобы предоставить научный метод оценки пропускной способности регулируемых перекрестков на разных этапах, таких как планирование, проектирование и эксплуатация, в данной статье анализируется масштабное исследование пропускной способности регулируемых перекрестков в разных странах, уделяя особое внимание обобщению предыдущих достижений в оценке пропускной способности регулируемых перекрестков. «Скорость потока насыщения и эффективное отношение зеленого сигнала являются двумя ключевыми параметрами для оценки пропускной способности: были проведены анализы по скорости потока насыщения, охватывающие ее различные формы моделей, методы измерения, базовую скорость потока насыщения и различные методы определения параметров коррекции; были разработаны, хронометрированы и запущены влияющие факторы, методы расчета и модели отношения зеленого сигнала для определения эффективного отношения зеленого сигнала для двух основных режимов управления сигналами. Наконец, были обсуждены потребности в исследованиях и изменяющиеся условия пропускной способности перекрестков с регулируемым сигналом, а также конкретные вопросы, которые необходимо решить в этой области исследований в городах, и было обсуждено направление развития исследований пропускной способности перекрестков с регулируемым сигналом. Результаты показывают, что текущие исследования пропускной способности перекрестков с регулируемым сигналом не учитывают условия вверх и вниз по течению. Дальнейшие исследования должны быть сосредоточены на расчете пропускной способности, анализе неопределенности в сложных транспортных условиях и оценке эффективности регулируемых перекрестков в условиях высокой загруженности.

Ключевые слова: методы, пропускная способность перекрестка, регулируемый перекресток, пропускная способность регулируемого перекрестка, интенсивность потока насыщения, эффективное время зеленого света.

Introduction.

With the continuous intensification of traffic congestion in cities, especially in large cities, and the increasing demands for sustainable development such as land and energy conservation and environmental protection, how to utilize limited resources to build and efficiently use road traffic systems has received increasing attention. Intersections are the bottlenecks of road traffic, and their capacity directly affects the carrying capacity of the entire traffic network. Correctly analysing and determining the capacity of an intersection, and subsequently designing or reconstructing the intersection based on this analysis, is of great significance for improving the intersection's capacity and enhancing its traffic conditions. This is also one of the core areas of research in the field of transportation.

Given that automobile traffic flow is the main component of traffic at general road intersections, this paper specifically reviews the research on its capacity. Road capacity is influenced by various factors such as traffic flow composition, vehicle performance, driving environment, driving behaviour, and road traffic management conditions. Therefore, the accurate calculation of road capacity is a very complex issue and has attracted widespread attention from experts and scholars in the field of traffic research worldwide. The research on the calculation methods for the traffic capacity of signal-controlled intersections has a long history in various countries, and these methods have been compiled into regulations or manuals to guide practical application. For example, the United States' "Highway Capacity Manual" (HCM) [2-3], Germany's "HBS" [4], Japan's "Road Traffic Capacity" [5], Canada's "CCG" [6], Australia's "Traffic Signals: Capacity and Timing Analysis" [7], Sweden's "Swedish Capacity Manual" [8], and Finland's "Capacity and Level of Service of Finnish Signalized Intersections" [9].

Foreign countries have also conducted a series of specialized studies on the traffic capacity of signal-controlled intersections, with related research starting as early as the 1980s and receiving funding from national and provincial-level projects. For example, Yang Paikin from Tongji University led the study "Traffic Capacity of Vehicle Conflict Points at Signalized Intersections," Yang Xiaoguang led the research "Study on Timing Control Signal Timing and Traffic Capacity Calculation Methods at Urban Road Flat Intersections," Guan Hongzhi from Beijing University of Technology led the study "Research on Traffic Capacity of Flat Intersections in Beijing," Rong Jian led the research "Study on Traffic Capacity and Traffic Experiment System of Urban Roads," Shao Chang Qiao authored "Research on Traffic Capacity of Urban Road Signalized Intersections" [11], Li Wenyuan from Southeast University led the study "Evaluation Methods of Urban Road Traffic Capacity and Traffic System," and Long Kejuan from Changsha University of Science and Technology led the research "Theoretical Study on Traffic Capacity Matching in Continuous and Interrupted Flow Transition Zones," among others.

In this paper, through the analysis of literature on the traffic capacity of road intersections in various countries, the research achievements in the field of "traffic capacity of signal-controlled intersections" are particularly summarized. Since the saturation flow rate and effective green signal ratio are the two most critical parameters for calculating traffic capacity, this paper focuses on reviewing the related research on these two key parameters. At the same time, in conjunction with the development of related research in the field of transportation, this paper looks forward to the future development direction of road intersection capacity research.

Calculation Methods

The main calculation methods for the traffic capacity of signal-controlled intersections are the following four:

① Saturation Flow Rate Method [3-11];
② Stop Line Method [12];
③ Give Way Line Method [13-15];
④ Conflict Point Method [14-17].

Among them, except for the conflict point method, which is mainly applied to signal-controlled intersections under permissive left-turn phases, the other three methods can generally be applied to typical signal-controlled intersections.

The saturation flow rate method is the method recommended in the U.S. HCM [3]. This method is based on the concept of lane groups. By determining the saturation flow rate and the effective green time ratio, the capacity of a given lane group can be calculated. The calculation formula is as follows:

$$C_{Approach} = s * \lambda \tag{1}$$

where:

$C_{Approach}$ is the capacity of the lane group at the signal-controlled intersection approach;

s is the saturation flow rate;

λ is the effective green time ratio.

The stop line method is the recommended approach in China's "Urban Road Design Code" (CJJ 37-90) [12]. This method first determines the design capacity of the straight-through lane, and the capacities of other functional lanes are then adjusted based on this. This method can be expressed as:

$$N_s = 3600 * \Psi_s * (\frac{t_g - t_1}{t_s} + 1)/C \tag{2}$$

In the formula:

N_s is the design capacity of a straight-through lane;

Ψ_s is the reduction factor for the capacity of a straight-through lane;

C is the signal cycle;

t_g is the green light duration within the signal cycle;

t_1 is the time taken for the first vehicle to start and pass the stop line after the signal turns green;

t_s is the average interval time for straight-through vehicles to pass the stop line.

By making appropriate transformations to equation (2), it is found that the 3600*Ψ_s/t_s part is equivalent to the saturated flow rate s, and the (tg-t_1 + t_s)/ C part is equivalent to the green time ratio λ. Therefore, equation (2) can be expressed as N_s = s* λ. Therefore, it can be considered that the stop line method, when calculating the capacity of straight lanes, is essentially still the saturated flow rate method.

The stop line method is another commonly used approach in China for calculating the traffic capacity of signal-controlled intersections. This method is based on the average time interval between two consecutive vehicles passing the stop line, and it provides calculation models for the traffic capacity of left-turn, straight, and right-turn lanes, as shown in equations (3) to (5).

$$N_L = \frac{3600}{C} * (t_{gL} - \frac{\vartheta_L}{2*a_L})/t_L \tag{3}$$

$$N_T = \frac{3600}{C} * (t_{gT} - \frac{\vartheta_T}{2*a_T})/t_T \tag{4}$$

$$N_R = \frac{3600}{t_R} \tag{5}$$

In the formula:

N_L, N_T, N_R represent the traffic capacities of dedicated left-turn, straight, and right-turn lanes, respectively;

t_{gL}, t_{gT} represent the signal durations for left-turn and straight movements within a cycle;

ϑ_L, ϑ_T represent the speeds of left-turn and straight vehicles, respectively;

a_L, a_T represent the average accelerations of left-turn and straight vehicles, respectively;

t_L, t_T, t_R represent the headway times of left-turn, straight, and right-turn vehicles passing the stop line, respectively.

By making appropriate transformations to equations (3) to (5), it is found that the parts 3600/t_L, 3600/t_T, and 3600/t_R are equivalent to the saturation flow rate s, and the parts (t_{gL} - $\vartheta_L 2a_L$)/C and (t_{gT} - $\vartheta_T 2a_T$)/C are equivalent to the green time ratio λ. Therefore, equations (3) to (5) can be expressed as N = sλ. Therefore, it can be considered that when the stop line method is used to calculate the intersection capacity, its essence is still the saturated flow rate method.

From the above analysis, it can be seen that the saturated flow rate method is the mainstream method for calculating the traffic capacity of signal-controlled intersections, with the saturated flow rate and effective green time ratio being its two key parameters. We strongly encourage authors to use this document for the preparation of the camera-ready. Please follow the instructions closely in order to make the volume look as uniform as possible (Moore and Lopes, 1999).

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Methods for determining saturation flow rate.

The saturation flow rate can generally be obtained through field measurements or model calculations.

2.1.1 Methods for Measuring Saturated Flow Rate

The methods for measuring the saturated flow rate mainly include the following three:

(1) Headway Method

This method first records the headway times of each queued vehicle passing the stop line. Then, the data of the initial few vehicles is discarded to avoid the impact of the green start-up loss time. Finally, the reciprocal of the average headway time is taken as the saturated flow rate. The key to this method lies in determining from which vehicle in the queue the traffic flow begins to enter the saturated flow state. HCM2000 [2] suggests removing the data of the first four vehicles and starting the calculation from the fifth vehicle. The study by Rahman et al. [18] found that the position of queued vehicles has a significant impact on the headway time. At different intersections, the position of queued vehicles entering a saturated flow state also varies.

(2) Regression Analysis Method [19-21]

By measuring the cumulative number of vehicles passing through the intersection at each moment during the green light period, and fitting it with linear regression, the slope obtained is the saturation flow rate.

(3) TRRL Method

The TRRL (Transportation and Road Research Laboratory) method is a method proposed by the British Road Research Laboratory [22]. This method divides the green light time into three phases, as shown in Figure 1. By calculating the ratio of the number of vehicles passing during the intermediate phase to the duration, the saturation flow rate is obtained. In Figure 1, s(t) represents the change in saturation flow rate over time; g is the effective green light duration; P_1 is the moment of lost time before the green light starts; P_2 is the moment of compensation time after the green light ends. Tarko et al. [23] found through investigation that during the green light period, the saturation flow rate increases rapidly within the first 6 seconds, and in the subsequent 20 seconds, the saturation flow rate does not fully stabilize but continues to increase slowly. The study suggests that the duration of the green light should be considered when predicting the saturation flow rate.

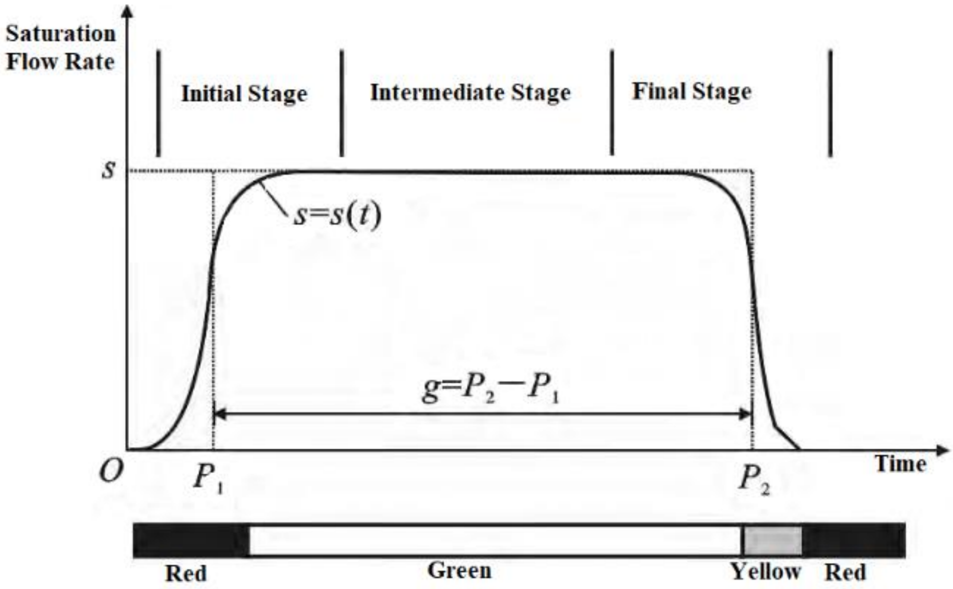

Figure 1. Variation of saturation flow rate with green time duration [16].

Model calculation of saturated flow rate.

2.2.1 Model Forms

The early saturation flow rate calculation models mainly have three forms: the multiplicative model, the additive model, and the reciprocal model, as shown in equations (6) to (8).

$$s = f * f_1 * f_2 * \ldots * f_n \tag{6}$$

$$s = s_0 + \Delta s_1 + \Delta s_2 + \Delta_3 + \cdots \tag{7}$$

$$s = \frac{3600}{h} = 3600/(h_0 + \Delta h_1 + \Delta h_2 + \cdots) \tag{8}$$

where:

s − saturation flow rate;

s_0 −base saturation flow rate;

$f, f_1, f_2, \ldots f_n$ −correction factors in the multiplicative model;

$\Delta s_1, \Delta s_2, \Delta s_3 \ldots$ − incremental factors in the additive model;

$h_0, h_1, \Delta h_1, \ldots$ − headway parameters in the reciprocal model.

Tarko et al. [23] conducted a study on model forms, and the results indicated that the multiplicative model and the reciprocal model performed better, while the additive model might produce erroneous results during calibration due to the large variance of the measured data samples. Currently, the multiplicative model is the commonly used model form.

2.2.2 Basic Saturation Flow Rate

With the continuous improvement of vehicle performance, the basic saturation flow rate shows a trend of continuous increase, as shown in Table 1. The research approach to determine the basic saturation flow rate can generally be carried out according to the steps shown in Figure 2 [24].

Table 1

Suggested Value of Basic Saturation Flow Rate in HCM

HCM 1965	HCM 1985	HCM 2000	HCM 2010	HCM 6 th	HCM 7 th
1320 1580	1800	1900	1900[a] 1750[b]	1900[a] 1750[b]	1900[a] 1750[b]

pc/h/ln

Note:

a refers to the situation where the city's population is greater than or equal to 250,000;

b refers to the situation where the city's population is less than 250,000.

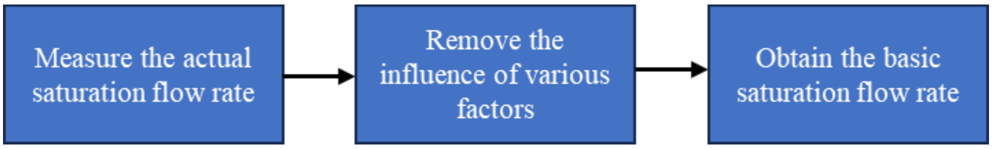

Fig. 2: Illustration of Study on Basic Saturation Flow Rate

The figure illustrates the study process for determining basic saturation flow rates:

2.2.3 Saturation Flow Rate Adjustment Parameters

The adjustment parameters for the saturation flow rate are the key focus in the study of signalized intersection capacity, primarily involving the road conditions, traffic conditions, and signal control conditions at the intersection.Specifically, it includes the following influencing factors:

(1) Impact of Lane Width

Research on lane width abroad has a long history, initially stemming from issues related to lane width on various levels of highways. Based on survey data, a lane width-speed impact model was developed, which in turn revealed the impact of lane width on traffic capacity.

Multiple studies based on empirical data [25-29] have shown that lane width is highly positively correlated with the saturation flow rate.Regarding the trend of increasingly narrowing lane widths on urban roads, especially at intersection approaches, the above research findings can be summarized as follows: When the lane width is less than 2.4 meters, vehicles find it difficult to operate normally; when the lane width is between 2.75 and 3.50 meters, the increase in saturation flow rate with the increase in lane width is quite significant; when the lane width exceeds 3.5 meters, the increase in saturation flow rate is minimal.

(2) Impact of Vehicle Type

Due to the differences in vehicle performance across various historical periods and different countries and regions, traditional research primarily focuses on empirical data to study the conversion coefficients (PCE) for various vehicle types [30-35]. Based on this, the large vehicle correction factor for traffic capacity is calculated.

The above studies are based on two assumptions: ① the correction factor for large vehicles is independent of the traffic direction; ② the vehicle type conversion factor is independent of the proportion of large vehicles.In this regard, Tarko et al. [23, 36-38] found that the vehicle conversion coefficient is also related to vehicle direction, traffic flow, and the proportion of large vehicles, and the situation where large vehicles travel in platoons should be considered.Additionally, when the proportion of large vehicles is high, the probability of them being the leading vehicles in the stopped traffic flow at intersections increases. This not only affects their saturation flow but also consumes more effective green light time.

(3) Impact of Bus Stops

Bus transportation has become an indispensable mode of transport.Since intersections are the main gathering points for pedestrian traffic, one approach is to place bus stops near the entrance of the intersection to facilitate passenger flow. However, the stopping of buses can cause subsequent vehicles to queue up, which will affect the traffic capacity of the entrance road.Regarding the correction of these influencing factors, considerations should include the number of lanes in the lane group, the arrival rate of buses and their stopping duration, and the distance between the bus stop and the intersection, among other factors [39-40].On this basis, Wu et al. [41] incorporated considerations of lane functions and signal control, making a more detailed classification of the impact on bus stops: ① The lane where the bus stop is located is a straight-right lane; ② The lane where the bus stop is located is a dedicated right-turn lane, and the right turn is uncontrolled; ③ The lane where the bus stop is located is a shared lane for buses and right-turn vehicles.

(4) Impact of Driver Behavior

The impact of driver behavior on the saturation flow rate has temporal and spatial characteristics.

In the past, research primarily focused on highway conditions, but by the end of the 20th century, some scholars began to consider this influencing factor in the calculation of the saturation flow rate at signal-controlled intersections.Zhou et al. [42-43] conducted a comparative analysis of the saturation flow rates in different urban areas, at different times, and on weekdays versus holidays. The results showed that the traffic efficiency at intersections in commercial areas is lower than in other regions, and the traffic efficiency at intersections during holidays is lower than on weekdays.

(5) Lane Utilization Impact

Lane utilization correction reflects the uneven distribution of traffic volume among lanes within a group of multiple lanes.Multiple studies based on empirical data [44-48] have found that the utilization rate of additional lanes at intersections is positively correlated with the length of the additional lanes and the peak 15-minute flow rate, and negatively correlated with the duration of the green light and the volume of right-turn traffic entering downstream of the intersection.

(6) Impact of Short Lanes

The correction of the impact of short lanes on the saturation flow rate mainly has three treatment methods: ① treating it as an independent entry lane [3, 6]. In these models, the focus is on the lane utilization rates of each lane, while ignoring the potential queueing blockage effects of short lanes.② Deterministic correction model [4, 7, 49].These models consider the queueing blockage that may be caused by short lanes due to length limitations, but they ignore their randomness. The determination of whether the short lane effect occurs is based on fixed judgment criteria, which means that the length of the short lane can cause a sudden change in traffic capacity at a certain critical point. Additionally, the models do not take into account the mutual interference between lanes.③ Probability-based correction models [50-53].These models mainly use probabilistic statistical theory to correct for short lanes, taking into account the length of the short lane and the randomness of queue blockages, making them closer to actual conditions.

(7) Impact of Pedestrians and Non-Motorized Vehicles

In the mixed traffic flow composed of motor vehicles, non-motorized vehicles, and pedestrians, the interaction and passage is an important characteristic of urban traffic in China.

Currently, the methods for quantitatively calculating the impact of pedestrians and non-motorized vehicles on the capacity of signal-controlled intersections mainly include the following categories: ① Saturation flow rate correction based on field measurements.This is a method that is widely adopted in the standards of various countries [5, 7, 11]. Using the flow rates of pedestrians and non-motor vehicles during green light hours as independent variables, it establishes a correction calculation model that reflects the interference of pedestrians and non-motor vehicles by studying the relationship between these flow rates and the proportion of time that the conflict area is available for motor vehicles [5, 7, 54] or the headway time of motor vehicle saturation [11, 55].② Methods based on the gap acceptance theory.The gap acceptance theory is one of the commonly used methods to describe the operational patterns of traffic conflict zones. Based on the priority of traffic flow directions, it determines parameters such as traffic flow arrival distribution, critical gap, and follow-up time through empirical measurements, thereby calculating the traffic capacity.Some scholars have applied this theory to the study of intersection capacity for pedestrians and non-motorized vehicles, providing methods for calculating capacity under certain assumptions of traffic rules [56-59].③ Simulation-based methods.With the increasing attention to pedestrian and non-motorized vehicle traffic, specialized simulation software for pedestrian and non-motorized vehicle flows has been continuously developed. For example, traffic simulation software such as Legion, TransModeler, and PTV have all added pedestrian modules.Chen Xiaoming et al. [60] studied the sensitivity of intersection capacity to average pedestrian and non-motorized vehicle flow under mixed traffic conditions based on the VISSIM simulation model.However, since computer simulations operate based on certain models (such as car-following models, social force pedestrian traffic flow models, etc.), they have their own limitations.

(8) Left Turn Traffic Impact

Left turn traffic adjustments reflect the geometric configuration of left turns (turning radius, lane width), the type of left turn lane (exclusive or shared), the type of signal phase (protected phase, permissive phase, or both protected and permissive phases), and the proportion of left turns on the saturation flow rate of the lane group.HCM 2000 [2] divides it into the following six situations and systematically provides correction models: dedicated left-turn lane + protected phase, dedicated left-turn lane + permissive phase, dedicated left-turn lane + both protected and permissive phases, shared through-left lane + protected phase, shared through-left lane + permissive phase, shared through-left lane + both protected and permissive phases.Especially for the calculation of the capacity of shared lanes with permissive left-turn phases, a specific method is provided, considering the impact of the initial green phase on the flow of opposing through traffic at saturated flow rates through the intersection on the passage of left-turning and through vehicles in the shared lane.

However, in the later phase of the green light when there is a gap for opposing through vehicles to merge, this method simply calculates the equivalent traffic capacity for that phase based on the proportion of left-turning vehicles and the equivalent through vehicle coefficient for left-turning vehicles, without considering the random arrival characteristics of left-turning vehicles or the blocking effect on through vehicles in the shared lane caused by queuing while waiting for the gap to merge.At the same time, this method does not consider the scenario where there is a left-turn waiting area in the case of a shared lane + protected phase.Xu et al. [61] proposed an improved model to address these issues, considering the impact of the length of the left-turn waiting area and the duration of the gap available for left-turn vehicles on the capacity of the straight-left lane.

(9) Right Turn Traffic Impact

The right turn traffic adjustment mainly reflects the impact of geometric conditions (such as turning radius). The extent of this impact is related to the type of right turn lane (dedicated right turn lane / shared straight and right turn lane), the proportion of right turn vehicles in the shared straight and right turn lane, and whether passage is allowed during the red light for straight traffic. HCM 2000 [3] systematically provides the correction model.

(10) Impact of Inbound and Outbound Traffic

Research on the traffic capacity of inbound and outbound traffic nodes has traditionally focused on their own traffic capacity. This includes studies on road segment traffic capacity, traffic capacity of unsignalized intersections, and traffic capacity of connecting roads. Zhao et al. [62], based on the research in literature [63] regarding the impact of ingress and egress traffic on road segment capacity, used fluctuation theory and queuing theory to establish a signal control intersection capacity correction model for ingress and egress traffic nodes located upstream and downstream of the intersection.The study indicates that when the inbound and outbound traffic is located near the signalized intersection, it will have a significant impact on the normal inflow and outflow of vehicles at the intersection. The extent of this impact is related to the number of lanes on the main road and the distance between the traffic nodes and the intersection.Moreover, among the six types of inbound and outbound traffic flows, the left turn from the main road, the right turn from the main road, and the left turn from the right-side inbound and outbound traffic nodes have the most significant impact.

(11) Impact of Weaving Areas

Weaving areas are an important component of the road system and have been a long-term focus of researchers, but there is relatively little research on the impact of weaving areas on intersection capacity.Yu Hao [64] pointed out that the traffic operation efficiency of the weaving section and the entry road can mutually influence each other, but did not provide a quantitative analysis model.Yang et al. [65] were the first to propose a calculation model for intersection capacity that considers the impact of the upstream weaving area.The study indicates that in situations where there is an interweaving area upstream of the intersection, the interweaving area determines the arrival rate of traffic flows from various directions at the intersection, while its own operational condition is influenced by the queue of vehicles at the red light of the intersection.Among all the factors, the length of the weaving area and the length of the intersection approach have the most significant impact on traffic capacity.

(12) Impact of Climate and Lighting Conditions

Some research findings [66-68] indicate that external factors such as climate and lighting conditions also affect the saturation flow rate and effective green light time at intersections.However, there are currently no universally accepted calibration results for these influencing factors.

(13) The Impact of Intelligent Transportation

With the increasing degree of traffic intelligence, the driving environment has undergone significant changes compared to traditional models. Scholars have begun to discuss the issue of traffic capacity at signal-controlled intersections in an information environment.For example, Andersen et al. [69] established an evaluation system for the impact of ITS systems on traffic capacity and service levels; Van Arem et al. [70] found through MIXIC microscopic simulation that intelligent vehicles operating in dedicated lanes can improve road capacity and traffic flow stability; Nekoui et al. [71] analyzed the effectiveness of intelligent vehicle-road systems in improving road traffic safety and capacity, prospectively studying the impact of vehicle-road collaborative systems on traffic in real-world applications, and proposed a mathematical framework for predicting multi-lane road system efficiency under such systems; Rakhha et al. [72-73] indicated that in a vehicle-road collaborative environment, drivers can make correct judgments and decisions based on accurate traffic environment information, thereby reducing the time and space intervals between vehicles.Therefore, as the intelligence level of vehicle-road collaboration systems increases, new changes in operational efficiency will occur.

Method for Determining Effective Green Signal Ratio

The effective green signal ratio is the ratio of effective green light time to cycle duration. It is another important aspect of calculating the traffic capacity of signalized intersections using the saturation flow rate method.Below, we will introduce the methods for determining the effective green signal ratio for two types of signal control: fixed-time and actuated.

3.1 Timed Control

When an intersection uses timed signal control (fixed cycle, fixed phase sequence), if the variation in lost time is not considered, the effective green signal ratio is a fixed value.The signal cycle and the duration of the green light can be directly obtained from the signal timing design results [3].Therefore, the effective green signal ratio λ can be calculated using equation (9).Among them, the effective green light time can be obtained through the displayed green light time, the pre-green light loss time, and the post-green light compensation time [74], as shown in equation (10).However, the current method for calculating effective green light time does not reflect the differences in loss time caused by the dynamic changes in the types of leading vehicles at the beginning of each green light cycle.

$$\lambda = \frac{g}{C} \tag{9}$$

$$g = G + e - l_1 \tag{10}$$

where:

g – effective green time (s);

C −Cycle length (s);

G −Green interval duration (s);

e − Extension of effective green(s);

l_1 − Start-up lost time(s).

3.2 Inductive Control

Since the signal timing scheme for intersections controlled by inductive signals can change according to variations in traffic conditions, the cycle length is not fixed. Additionally, the green light duration for each phase is interdependent, making it impossible to directly determine the average cycle length and green light duration from the model.

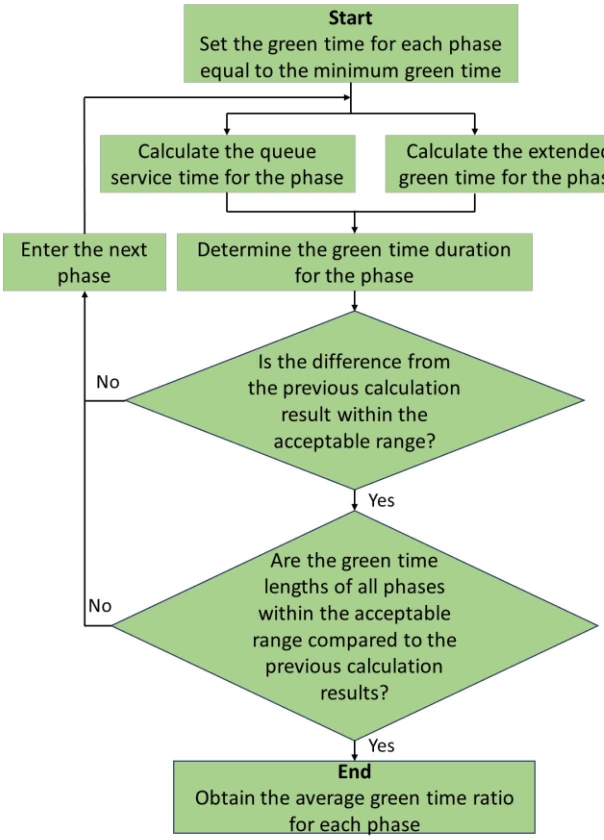

Figure 3. Algorithm for calculating the ratio of green signals at actuated-controlled intersections

$$g_s = f_q \, \frac{q_r * r}{s - q_g} \tag{11}$$

$$g_e = \frac{e^{\lambda(e_0 + t_0 - \Delta)}}{\varphi * q} - \frac{1}{\Theta} \tag{12}$$

where:

g_s — queue service time (s);

g_e — green extension time (s);

f_q — correction coefficient for the length of the vehicle queue, indicating the impact of vehicle arrival randomness;

q_r — vehicle arrival rates during red light periods, respectively;

q_g — vehicle arrival rates during green light periods, respectively;

r — effective red time;

q — vehicle arrival rate over the entire cycle;

e_0 — set unit extension time;

t_0 — time vehicles occupy the detector;

Δ — minimum headway time between arriving vehicles;

φ — proportion of vehicles traveling freely;

Θ — number of vehicles passing through the lane group per second.

Prevedouros [75] proposed that if the green signal ratio is to be obtained through actual measurement, it requires a period of continuous and stable measurement, with data collected periodically. Courage et al. [76] proposed an iterative calculation method for signal cycle and effective green light time under inductive signal control. They set the minimum green light duration as the initial state, calculated the queue service time for each phase [Equation (11)] and the green light extension time [Equation (12)], and through repeated iterations, obtained the green light time for each phase, thereby determining the average green signal ratio. The calculation process is shown in Figure 3.

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Prospects for Research Development Directions

With the gradual deepening of understanding of the connotation of traffic capacity and its influencing factors, as well as the changes and developments in intelligent transportation technology, vehicle technology, and operating environment, traffic capacity has remained a hot topic for over 100 years of research. The scientific calculation of traffic capacity and the calculation of traffic capacity for different purposes are still hot issues. Future research directions may focus on the following aspects:

(1) Combining the upstream inflow and downstream outflow conditions of the intersection, the calculation of traffic capacity under fluctuating saturation flow rates [77]. Current research on the traffic capacity of signal-controlled intersections still primarily focuses on the road, traffic, and signal control conditions at the stop line section. This is partly because foreign countries place more emphasis on traffic design [78], with traffic design coming before road design, and the relevant standards and design requirements being stricter. Additionally, the conditions for entering and exiting intersections are relatively reasonable, and driving is more regulated. Therefore, under these conditions, the capacity calculation does not take into account the impact of upstream and downstream road traffic conditions. But in our cities, the geometric design of road space and signal timing are disconnected. Traffic design has only been introduced in recent years, and the traffic flow patterns are not adequately considered in road design. Observation has found that in the central streets of our cities, the saturation flow rate during the green light phase at road intersections exhibits significant fluctuations, primarily due to the influence of traffic conditions on the upstream and downstream roads of the intersection. Therefore, in future studies on the traffic capacity of signal-controlled intersections, the research perspective should be expanded to include the upstream and downstream of the stop line, and the influencing factors and mechanisms should be analyzed to make the traffic capacity calculation results more in line with the actual situation in our cities.

(2) Research on the calculation methods for traffic capacity under complex traffic environments. Compared to road traffic abroad, the phenomenon of mixed traffic in our countries urban roads is particularly common and severe, and there are no effective measures to address it. This includes: the mixing of motor vehicle performance, the mixing of vehicle types, the mixing of different modes of transportation, the mixing of different road design patterns, and the mixing of traffic management methods. Therefore, for the study of traffic capacity at signal-controlled intersections, it is important to consider regional characteristics, including traffic flow characteristics, traffic operation rules, road network features, road design characteristics, and driver behavior. Additionally, abnormal weather conditions such as rain, snow, and ice have a significant impact on the normal flow of traffic. In recent years, the severe traffic congestion observed in many cities during natural disasters reflects, to some extent, the mismatch between infrastructure and traffic. Therefore, considering the impact of abnormal weather on traffic capacity calculation methods is also an important research direction.

(3) Traffic capacity estimation models in information environments. With the development and application of intelligent transportation systems and vehicle-road collaboration systems in various countries, the road operating environment is gradually moving towards a holographic era. Studying the traffic operation conditions at intersections in a holographic environment, as well as the characteristics and changing features of traffic flow, and accurately reflecting their impact on traffic capacity, will be another development direction in the research of intersection traffic capacity.

(4) Uncertainty analysis of traffic capacity. For established road traffic facilities, capacity generally refers to the traffic flow that can be repeatedly achieved during peak periods with sufficient traffic demand. However, research on issues such as traffic flow "jumps" and sudden traffic interruptions all point to the randomness of traffic capacity. Currently, research in this area mainly focuses on expressways. Whether signal-controlled intersections exhibit similar characteristics and what analysis methods should be used require further investigation.

Conclusions.

The saturation flow rate method is the mainstream method for calculating the capacity of signal-controlled intersections. Both the "Stop line method" and the "Give way line method " use the saturation flow rate multiplied by the green ratio to calculate the capacity of signal-controlled intersections. Essentially, these two methods are still based on the saturation flow rate method.

Current research on the capacity of signal-controlled intersections primarily focuses on the road, traffic, and signal control conditions at the stop line section. Greater emphasis should be placed on considering the upstream and downstream conditions of the intersection.

With the evolution and development of intelligent transportation technologies, vehicle technologies, and operational environments, the study of intersection capacity is an ongoing and adaptive process. In the future, calculating intersection capacity under special conditions and conducting uncertainty analyses will be important directions for research. This includes considerations for mixed traffic environments, adverse weather, informational environments and criterion for evaluating the effectiveness of a signaled intersection.

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