A Study on Traffic Flow at Urban Road Intersections Based on Queuing Theory

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Abstract

With the popularization of private cars, the congestion of urban roads has become more serious, especially at road intersections, and traffic jams have occurred from time to time. Therefore, it is of great significance to study the traffic flow at road intersections to alleviate traffic pressure at intersections. In this paper, taking the road intersection of Huixin East Bridge and Huixin East Street in Chaoyang District of Beijing as an example, using the follow-up data, a queuing model is established for the queuing process of traffic flow at the intersection, and the queueing knowledge is applied to the intersection. The analysis of traffic flow shows that the queuing theory model is in line with the actual vehicle queuing situation, and it has certain practical guidance for the planning and evaluation of intersections.

Keywords—*Road intersection; Car-following; Traffic flow; Queuing theory*

I. INTRODUCTION

With the continuous improvement of people's living standards, private cars have become an important means of transportation for many families. As a result, more and more crowded traffic conditions have arisen, especially at road intersections, where congestion is particularly evident. The intersection of urban roads is formed by the convergence of multiple roads. It is the place where the flow of people and traffic flows gathers. It is a crucial link in the transportation system and is also the most prone to congestion. Traffic jams at road intersections are commonplace in Beijing, where there are a large number of floating populations and traffic flows. This has also led to a significant reduction in the efficiency of vehicles, which not only makes it easier to disrupt traffic order, but also causes exhaust emissions to cause air pollution. This requires us to effectively alleviate the current congestion situation, not just by limiting line.

In traffic engineering analysis, it can be roughly divided into two kinds of research [1]. One is the study of vehicle operation based on the car following and changing lanes, which is mainly applied to traffic flow analysis on the road section. The other is based on the queuing analysis theory and the traffic fluid mechanics simulation theory, from the control of the intersection. The two studies have similarities and there is no absolute division. In this paper, based on the car-following, based on field survey data, the traffic congestion situation is analyzed from the perspective of queuing theory.

II. APPLICATION OF QUEUING THEORY IN TRAFFIC FLOW

The queuing theory originated in the telephone problem at the beginning of the 20th century, and now the queuing theory has developed vigorously. It is widely used in many service systems and is an important part of operations research. In 1936, Adams would queue up to consider the issue of pedestrian delays at intersections without traffic signals, after which queuing theory became more and more widely used in traffic engineering. In road traffic systems, there are a lot of queuing processes, such as intersections, toll stations, and traffic control. The queuing theory mainly studies the waiting time and the probability distribution of the queue length so as to reasonably coordinate the relationship between the "service object" and the "service system" so that it can meet the requirements of the "service target" and save the service system to the utmost extent. Funding. This article is based on the queuing theory and takes the intersection of Huixin East Bridge and Huixin East Street in Chaoyang District of Beijing as an example to conduct an in-depth study on the queuing process of traffic flow at intersections. The actual traffic control and planning are a guiding role.

The three components of the queuing system [2]: input procedures, queuing rules, and service methods. The input process refers to the arrival of various types of vehicles in accordance with the law, which can be divided into three parts: the total number of customers (vehicle source), arrival mode, and service organization; the queuing rule refers to the order in which the arriving vehicles stay at the intersection. Divided into loss system, waiting system and hybrid system; service method refers to how many lanes can be accepted at the same time, how much time it takes, can be divided into: (1) whether the service desk is in series or in parallel; (2) what kind of service time is required to follow? The probability distribution, whether each required service time is independent of each other, is a composition of a queuing system such as a batch service or a single service, as shown in Fig.1.

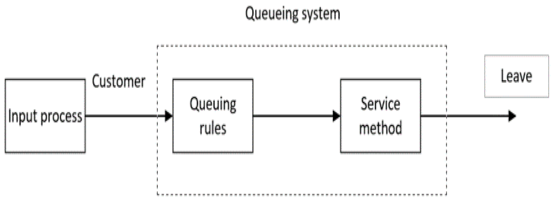

Fig 1: The composition of the queuing system

The queuing problem is to calculate the basic quantitative indicators of the queuing system, to study the status of the system, that is, the number of customers in the system, so as to analyze the operating efficiency of the system, estimate the service ideology of the system, and determine the optimal value of the system characteristics. The system can be divided into single-channel queuing service system and multi-channel queuing system. This article studies the multi-channel queuing system.

The performance indicators in the queuing theory can be divided into two types: one is the instantaneous performance index, which refers to the status feature of the queuing system at any moment; the second is the stability performance index, which refers to the queuing system where the queuing system is located after a sufficiently long running time. At this time, the performance indicators no longer change with time, the working state is stable. This article focuses on stability performance indicators.

III. INTERSECTION MULTI-CHANNEL QUEUING SYSTEM

A. Queuing Theory Based Intersection Analysis Model

If it is assumed that the arrival of the vehicle is continuous, the vertical axis represents the accumulated vehicle that arrives, and the horizontal axis represents time [3]. The arrival, departure, and queuing process of the vehicle at the signalized intersection can be analyzed from Fig. 2.

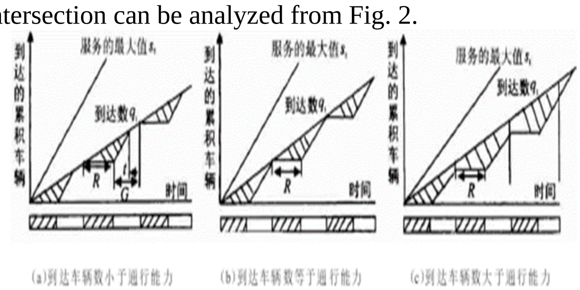

Fig2: Queuing Analysis Image at Signalized Intersection Based on Queuing Theory

As can be seen from Figure 2-1, the queuing of vehicles arriving during the red light period in Figure 2-1 (a) and (b) can be released within a green time. In both cases, cumulative vehicles form on the time axis. The image is a triangle. In Figure 2-1 (c), the number of arriving vehicles is greater than the capacity. Therefore, the number of vehicles arriving during the red light cannot be released within one green time. Some vehicles need to be queued twice and wait until the next cycle. Released. In this case, the queue is longer and the delay is larger. This is a case where the traffic is relatively crowded. At this time, the image formed by the cumulative vehicle on the time axis is a polygon.

B. Multi-channel queuing system

Under normal circumstances, intersection roads are mostly multi-lane, single-lane queuing system (M/M/1) is not introduced in this article, focusing on multi-channel queuing systems, also known as M/M/N systems. Suppose the average customer arrival rate is λ, the average output rate is μ, the average service time per service desk is 1/μ, and the ratio is denoted as ρ=λ/μ, then the traffic intensity of the M/M/N system (use factor) is ρ/N. When ρ/N<1, the system is stable, and when ρ/N>1, the system is unstable.

（1）The probability of no vehicle in the system：

$$P_0 = \frac{1}{\sum_{k=0}^{N-1} \frac{\rho^k}{k!} + \frac{\rho^k}{N!(1-\rho/N)}}$$

（2）The probability of having k cars in the system：

$$p_k = \frac{\rho_k}{k!} P_0 (k < N),$$

$$p_k = \frac{\rho_k}{N!N^{K-N}} P_0 (k \geq N)$$

（3）Average queue length in the system：

$$\bar{q} = \frac{\rho^{N+1}}{N!N} \bullet \frac{P_0}{(1-\rho/N)^2}$$

（4）Average number of vehicles in the system：

$$\bar{n} = \bar{q} + \rho$$

（5）Average consumption time in the system：

$$\bar{d} = \frac{\bar{q}}{\lambda} + \frac{1}{\mu}$$

（6）Average waiting time：

$$\omega = \frac{\bar{q}}{\lambda}$$

IV.TRAFFIC FLOW CALCULATION

A. Traffic Survey Overview

Traffic survey is the use of objective methods to measure road traffic flow and its related phenomena, and then analyze the survey data obtained, thus grasp the operational characteristics of the traffic flow, existing problems and changes in rules, and set up traffic management facilities and management measures Formulate scientific decision-making basis[4]. The contents of this traffic investigation included the actual survey of the geometric structure, traffic flow, and saturation flow of the Huixin East Bridge intersection.

B. Survey of road network geometry

Surveys of road network geometry include surveys of lane distribution, lane direction, number of lanes, width of each lane, etc.

Huixin Bridge intersection includes the north, south, east, and west of the four directions of the import and export lanes. The south entrance has two left-turn lanes, two straight lanes and one right-turn lane. The north entrance, east entrance and west entrance have set up two left-turn lanes, one straight-ahead lane and one right-right lane. The south exit and the north exit are both 2 lanes, and the east exit and west exit are 3 lanes. The width of each lane is 3.5 meters. The road network diagram is shown in Fig. 3.

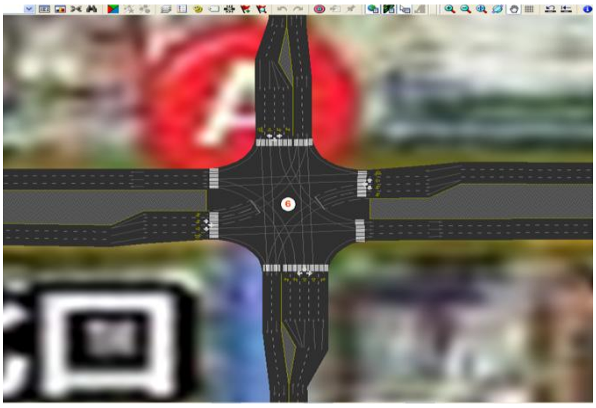

Fig.3: Huixin East Bridge Intersection Road Network

According to the distance measurement on Baidu map, the entrance and exit of the Huixin East Bridge intersection is approximately 40 meters apart. Generally, the speed of the intersection passing through the intersection is approximately 33 kilometers per hour. Based on the normal speed, the time taken by the car to pass through the intersection is approximately 4 seconds.

C. Traffic flow and saturation flow survey

1) Survey content

In order to ensure that the survey data is more relevant to the actual situation, observations were taken arbitrarily for two days on the working day. The normal traffic survey time period was from 10 am to 11 am, and the peak saturation traffic survey time was from 7 am to 9 pm. Investigate one of the main intersections of Huixin East Street: Huixin Bridge.

First of all, we need to complete the investigation of Huixin East Bridge crossing the road network geometry, including specific settings and lane width of each lane of imports; Second, the need to investigate each direction Huixin East Bridge intersection imports turn left, go straight and The number of vehicles turned to the right was recorded in sub-models (large, medium, and small cars) and traffic was obtained for one hour. In addition to the amount of traffic for each entrance at the intersection, it is necessary to investigate and calculate the saturation flow at each entrance to the intersection.

2) Survey Methods

This article studies the single road intersection, the most important thing is to measure the amount of traffic in each direction of the intersection. Because the traffic conditions at the intersection are more complicated than the road sections and the traffic volume is relatively large, manual counting and video recording methods are used to investigate the traffic volume at the intersection. During the observation process, the entrance of each intersection requires one or more observers. For intersections with large traffic volume, it is advisable to have at least three observers at each intersection to observe the traffic flow of left turn, straight line and right turn. Due to limited observers, large intersections and limited observation conditions, it was decided that each person was responsible for an import. Standing at a commanding height near each entrance of the intersection, using a camera or mobile phone with a video function, shooting at the same time Traffic flow, and then later carried out sub-model statistics. Through the video playback, according to the change of the position of each vehicle in the intersection at different time intervals, the traffic volume in different directions is calculated manually.

3) Traffic flow statistics

According to the length of the vehicle, the vehicles are categorized as large cars, medium cars, and small cars. The coefficient of a large-sized vehicle is 3, that of a medium-sized vehicle is 1.5, and that of a small-sized vehicle is 1[7]. The turnover of the entrances of the intersections during the survey period from 10 am to 11 am is shown in Table 4-1 to Table 4-4.

Table 4-1 Huixin East Bridge intersection north entrance turn flow

Project	Small car	Medium car	Large car
Left turn traffic (vehicle/hour)	420	48	12
Straight traffic (vehicle/hour)	444	72	24
Right turn traffic (vehicle/hour)	280	36	0

Table 4-2 Huixin East Bridge intersection south entrance turn flow

Project	Small car	Medium car	Large car
Left turn traffic (vehicle/hour)	380	36	12

Straight traffic (vehicle/hour)	472	24	0
Right turn traffic (vehicle/hour)	248	30	0

Table 4-3 Huixin East Bridge intersection east entrance turn flow

Project	Small car	Medium car	Large car
Left turn traffic (vehicle/hour)	272	54	0
Straight traffic (vehicle/hour)	300	90	12
Right turn traffic (vehicle/hour)	144	12	0

Table 4-4 Huixin East Bridge intersection west entrance turn flow

Project	Small car	Medium car	Large car
Left turn traffic (vehicle/hour)	356	48	0
Straight traffic (vehicle/hour)	208	48	0
Right turn traffic (vehicle/hour)	160	18	0

The traffic flow at each intersection at the intersection is shown in Fig.4.

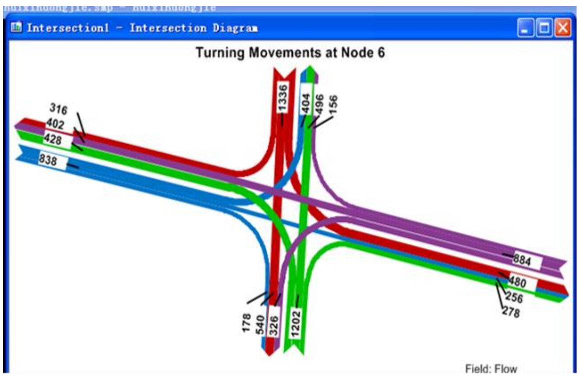

Fig4: Huixin East Bridge crossing the import and export traffic image

Saturation flow rate calculation method: Measure the time and vehicle type of the saturated traffic flow of each vehicle passing through the entry stop line. Calculate the headway distance and the headway time interval of the most closely followed team in each cycle after the fourth vehicle per cycle. Saturation Flow = 3600 seconds / average saturation time headway [5]. The specific results are shown in Fig.5 and shown in Fig.6.

东进口各车道饱和流量调查

车道名称	测量周期	紧跟的车队中第1辆车的通过时刻（s）	紧跟的车队中最后一辆车的通过时刻（s）	最后一辆车与第1辆车通过的时间间隔（s）	车队中的小型车数量（折算系数为1）	车队中的中型车数量（折算系数为1.5）	车队中的大型车数量（折算系数为3）	车队折合的小型车总数（小型车当量）	饱和车头时距（s）	平均饱和车头时距（s）	饱和流量（辆/h）
左转1	1	6	22	16	6	1	0	7.5	2.13	2.33	1545
	2	15	27	12	5	0	0	5	2.40		
	3	11	31	20	6	2	0	9	2.22		
	4	24	39	15	7	0	0	7	2.14		
	5	13	24	11	5	0	0	4	2.75		
左转2	1	8	20	12	5	0	0	5	2.40	2.36	1525
	2	22	38	16	4	2	0	7	2.29		
	3	11	24	13	4	1	0	5.5	2.36		
	4	9	26	17	7	0	0	7	2.43		
	5	27	41	14	6	0	0	6	2.33		
直行	1	14	32	18	5	2	0	8	2.25	2.24	1607
	2	26	40	14	5	1	0	6.5	2.15		
	3	7	18	11	5	0	0	5	2.20		
	4	27	43	16	7	0	0	7	2.29		
	5	18	33	15	5	1	0	6.5	2.31		
直右	1	13	28	15	5	1	0	6.5	2.31	2.35	1532
	2	24	41	17	7	0	0	7	2.43		
	3	9	26	17	6	1	0	7.5	2.27		
	4	29	41	12	5	0	0	5	2.40		
	5	10	24	14	6	0	0	6	2.33		

西进口各车道饱和流量调查

车道名称	测量周期	紧跟的车队中第1辆车的通过时刻（s）	紧跟的车队中最后一辆车的通过时刻（s）	最后一辆车与第1辆车通过的时间间隔（s）	车队中的小型车数量（折算系数为1）	车队中的中型车数量（折算系数为1.5）	车队中的大型车数量（折算系数为3）	车队折合的小型车总数（小型车当量）	饱和车头时距（s）	平均饱和车头时距（s）	饱和流量（辆/h）
左转1	1	11	23	12	4	1	0	5.5	2.18	2.26	1593
	2	28	45	17	6	1	0	7.5	2.27		
	3	17	28	11	5	0	0	5	2.20		
	4	22	37	15	5	1	0	6.5	2.31		
	5	9	23	14	6	0	0	6	2.33		
左转2	1	19	31	12	5	0	0	5	2.40	2.35	1532
	2	26	42	16	5	1	0	6.5	2.46		
	3	8	25	17	6	1	0	7.5	2.27		
	4	14	30	16	7	0	0	7	2.29		
	5	21	35	14	6	0	0	6	2.33		
直行	1	12	26	14	6	0	0	6	2.33	2.33	1545
	2	27	44	17	6	1	0	7.5	2.27		
	3	18	33	15	6	0	0	6	2.50		
	4	13	31	18	8	0	0	8	2.25		
	5	29	45	16	4	2	0	7	2.29		
直右	1	14	26	12	5	0	0	5	2.40	2.35	1532
	2	31	45	14	6	0	0	6	2.33		
	3	23	35	12	5	0	0	5	2.40		
	4	19	34	15	5	1	0	6.5	2.31		
	5	9	23	14	6	0	0	6	2.33		

Fig5: Huixin East Bridge East and West entrance saturation flow chart

南进口各车道饱和流量调查

车道名称	测量周期	紧跟的车队中第1辆车的通过时刻（s）	紧跟的车队中最后一辆车的通过时刻（s）	最后一辆车与第1辆车通过的时间间隔（s）	车队中的小型车数量（折算系数为1）	车队中的中型车数量（折算系数为1.5）	车队中的大型车数量（折算系数为3）	车队折合的小型车总数（小型车当量）	饱和车头时距（s）	平均饱和车头时距（s）	饱和流量（辆/h）
左转1	1	10	20	10	4	0	0	4	2.50	2.34	1538
	2	26	46	20	4	3	0	8.5	2.35		
	3	12	30	18	5	0	1	8	2.25		
	4	15	30	15	5	1	0	6.5	2.31		
	5	29	45	16	7	0	0	7	2.29		
左转2	1	9	25	16	4	2	0	7	2.29	2.39	1506
	2	25	38	13	5	0	0	5	2.60		
	3	14	31	17	7	0	0	7	2.43		
	4	22	37	15	5	1	0	6.5	2.31		
	5	11	25	14	6	0	0	6	2.33		
直行1	1	13	28	15	5	1	0	6.5	2.31	2.35	1532
	2	27	43	16	4	0	1	7	2.29		
	3	14	26	12	5	0	0	5	2.40		
	4	30	43	13	4	1	0	5.5	2.36		
	5	24	36	12	5	0	0	5	2.40		
直行2	1	9	23	14	6	0	0	6	2.33	2.41	1494
	2	12	27	15	5	1	0	6.5	2.31		
	3	31	46	15	3	2	0	6	2.50		
	4	12	27	15	3	0	1	6	2.50		
	5	27	39	12	5	0	0	5	2.40		
右转	1	20	33	13	5	0	0	5	2.60	2.49	1445
	2	15	30	15	5	1	0	6.5	2.31		
	3	11	25	14	4	1	0	5.5	2.55		
	4	28	40	12	5	0	0	5	2.40		
	5	16	29	13	5	0	0	5	2.60		

北进口各车道饱和流量调查

车道名称	测量周期	紧跟的车队中第1辆车的通过时刻（s）	紧跟的车队中最后一辆车的通过时刻（s）	最后一辆车与第1辆车通过的时间间隔（s）	车队中的小型车数量（折算系数为1）	车队中的中型车数量（折算系数为1.5）	车队中的大型车数量（折算系数为3）	车队折合的小型车总数（小型车当量）	饱和车头时距（s）	平均饱和车头时距（s）	饱和流量（辆/h）
左转1	1	11	27	16	7	0	0	7	2.29	2.30	1565
	2	23	44	21	6	0	1	9	2.33		
	3	30	48	18	5	2	0	8	2.25		
	4	15	30	15	5	1	0	6.5	2.31		
	5	29	43	14	6	0	0	6	2.33		
左转2	1	18	32	14	6	0	0	6	2.33	2.33	1545
	2	26	42	16	5	1	0	6.5	2.46		
	3	9	25	16	4	2	0	7	2.29		
	4	32	47	15	5	1	0	6.5	2.31		
	5	24	42	18	8	0	0	8	2.25		
直行	1	8	28	20	6	0	1	9	2.22	2.21	1629
	2	20	36	16	6	1	0	7.5	2.13		
	3	17	36	19	7	1	0	8.5	2.24		
	4	15	35	20	6	0	1	9	2.22		
	5	33	51	18	5	2	0	8	2.25		
直右	1	16	30	14	5	1	0	6.5	2.15	2.22	1622
	2	29	43	14	6	0	0	6	2.33		
	3	12	29	17	5	2	0	8	2.13		
	4	31	44	13	4	1	0	5.5	2.36		
	5	22	37	15	7	0	0	7	2.14		

Fig6: Huixin East Bridge South and North entrance saturation flow chart

Saturation flow rates are shown in Table 4-5 to Table 4-8. The relationship between the volume of imported traffic at each intersection and the saturation flow is shown in Fig.7.

Table 4-5 Huixin East Bridge North entrance lane saturation flow questionnaire

Lanes	Saturation flow(pcu)	Total
Left turn lane 1 (vehicle/hour)	1565	3110
Left turn lane 2 (vehicle/hour)	1545	
Straight lane (vehicle/hour)	1629	3251
Straight and right lane (vehicle/hour)	1622	

Table 4-6 Huixin East Bridge South entrance lane saturation flow questionnaire

Lanes	Saturation flow(pcu)	Total
Left turn lane 1 (vehicle/hour)	1538	3044
Left turn lane 2 (vehicle/hour)	1506	
Straight Lane 1 (vehicle/hour)	1532	3026
Straight Lane 2 (vehicle/hour)	1494	
Turn right lane (vehicle/hour)	1445	1445

Table 4-7 Huixin East Bridge East entrance lane saturation flow questionnaire

Lanes	Saturation flow(pcu)	Total
Left turn lane 1 (vehicle/hour)	1545	3070
Left turn lane 2 (vehicle/hour)	1525	
Straight lane (vehicle/hour)	1607	3139
Straight and right lane (vehicle/hour)	1532	

Table 4-8 Huixin East Bridge West entrance lane saturation flow questionnaire

Lanes	Saturation flow(pcu)	Total
Left turn lane 1 (vehicle/hour)	1593	3125
Left turn lane 2 (vehicle/hour)	1532	
Straight lane (vehicle/hour)	1545	3077
Straight and right lane (vehicle/hour)	1532	

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Phase	First phase		Second phase		Third phase		Fourth phase	
Entrance	South (Straight /Right)	North (Straight/Right)	South (Left)	North (Left)	East (Straight/ Right)	West (Straight/ Right)	East (Left)	West (Left)
Number of vehicles q (vehicles/ hour)	774	856	428	480	558	434	326	404
Saturation flow s (vehicle/hour)	4471	3251	3044	3110	3139	3077	3070	3125
Traffic ratio	0.17	0.26	0.14	0.15	0.18	0.14	0.11	0.13
Maximum flow ratio	0.26		0.15		0.18		0.13	
The sum of the maximum flow ratio of each phase	0.72							
Remark	The sum of the maximum flow ratio of each phase cannot be greater than 0.9.							

Fig7: Huixin East Bridge intersection traffic phase flow ratio calculation

Calculate the capacity of the intersection[6]:

$$Q = 0.26 \times 4471 + 3251 + 0.15 \times 3044 + 3110 + 0.18 \times 3139 + 3077 + 0.13 \times 3070 + 3125 = 4855.05(pcu/h)$$

V. QUEUEING MODEL TO MEASURE VEHICLE QUEUING AT PEAK TIMES

According to the survey data, vehicles arriving at intersections are random, subject to Poisson distribution [8], and the saturated vehicle flows from the intersections are shown in Table 4-5 to Table 4-8. It is assumed that the saturated traffic volume of each inlet is 6000 pcu/h. According to the method of calculating the continuous traffic flow, the average saturation headway time can be regarded as the average service time $1/\mu = 2.3s$, and the corresponding index is calculated according to the single-channel multi-channel (M/M/4 system). Answers are as follows:

$$\lambda = \frac{6000}{3600} = \frac{5}{3}(pcu/s),$$

$$\mu = 1/2.3(pcu/s)$$

$$\rho = \frac{\lambda}{\mu} = \frac{11.5}{3}, \quad \frac{\rho}{N} = \frac{11.5}{12} < 1$$

$$P(0)=\frac{1}{\sum_{k=0}^{3}\frac{\left(\frac{11.5}{3}\right)^{k}}{k!}+\frac{\left(\frac{11.5}{3}\right)^{4}}{4!\left(1-\frac{11.5}{12}\right)}}=0.004$$

$$\bar{q}=\frac{\left(\frac{11.5}{3}\right)^{5}}{4!\times 4}\times\frac{0.004}{\left(1-\frac{11.5}{12}\right)^{2}}=19.8(\text{pcu})\approx 20(\text{pcu})$$

$$\bar{n}=\bar{q}+\rho=24(\text{pcu})$$

$$\bar{d}=\frac{\bar{q}}{\lambda}+\frac{1}{\mu}=7.5s$$

$$\omega=\frac{\bar{q}}{\lambda}=5.2(s/\text{pcu})$$

In fact, when traffic peaks, the number of queuing vehicles in each lane of a road intersection is roughly the same as that calculated by the queuing theory model, which also proves that the queuing theory has a guiding effect on the actual traffic conditions.

VI. SUMMARY

Through calculations, the results of queuing theory knowledge are roughly in line with the actual situation, which has a reference value for the calculation of traffic volume. For saturated traffic flow, the probability of not requiring queuing is quite small, and the queue length is also long. It shows that the signal control scheme at the intersection needs to be improved. According to the actual situation, due to the large north-south traffic flow, the traffic efficiency can be improved by increasing the north-south lanes or extending the north-south green light time.

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