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Intersection capacity based on driver's visual characteristics

Lu Jian Chen Weiwei Fan Hongjing

(Key Laboratory of Transportation Planning and Management of Jiangsu Province, Southeast University, Nanjing 210096, China)

Abstract: In order to reflect the influence of the drivers' characteristic differences on intersection capacity under a mixed traffic flow, a driver correction coefficient for the intersection capacity calculation according to the driver's visual characteristics is proposed. First, the parameters of the driver's visual characteristics at some real roads, including gaze fixation distribution, mean fixation duration, visual angle distribution and some other parameters at intersections, are collected. Then, the relationship between the traffic flow rate at intersections and the parameters of driver eye movements are established. The analytical results indicate that when the traffic flow is unsaturated, the parameters of driver eye movements change relatively little; however, when the traffic flow is saturated, the parameters of driver eye movements change drastically. Finally, the saturation-flow-rate model is modified according to the parameters of driver eye movements; thus, a capacity model of intersections considering the driver's visual characteristics is obtained.

Key words: intersection; driver's visual characteristics; saturation-flow-rate; capacity; compensation factor

At present, the intersection capacity is usually calculated by using the saturation method which takes into account road factors (such as lane width, road slope, intersection type, etc.), traffic factors (such as vehicle composition, turning-vehicle proportion, etc.), and environmental factors(such as region characteristics, parking situation, bus stops, pedestrian crossings, etc.). However, it ignores the influence of driver factors on intersection capacity. In fact, a driver's psychological tension and reaction ability to traffic information affect traffic flows at intersections to some extent. So, as an important participant in road traffic, a driver's behavior has an inconvenient influence on intersection capability. Because driver information is mainly from vision when crossing an intersection[1], studying the relationship between driver behavior (especially visual behavior) and intersection capacity will be significantly important in indicating the user-friendly design of traffic facilities, improving intersection efficiency, and reducing traffic accidents.

A driver's dynamic visual characteristics mainly include gaze fixation frequency, gaze fixation distribution, visual angle deviation, visual angle horizontal/vertical distribution, fixation duration, eye movement speed and so on[2]. In this paper, for simplicity, we consider three primary components as follows: 1) Gaze fixation distribution; 2) Mean fixation duration; 3) Visual angle distribution. We have conducted some experiments on real roads to study the influence of these three parameters on traffic flows, and modify the saturation-flow-rate model that is used to calculate intersection capacity. Therefore, we propose a new model to calculate intersection capacity considering drivers' visual characteristics.

1 Variation Rule of Drivers' Visual Characteristics at Intersection

1.1 Gaze fixation distribution

The process of eye movement can be described intuitively by gaze fixation distribution. When the traffic flow at an intersection is stable or changes little, a driver will have surplus energy [3] after completing the task of controlling the vehicle and observing the surrounding environment, therefore, the driver's visual characteristics are stable and the gaze fixation distribution is wide, continuous and steady (as shown in Fig. 1). With the increase in traffic flow, vehicle headway becomes smaller. Since drivers do not have surplus energy to observe the surrounding environment, the distribution area of a driver's gaze fixation is smaller and chaotic (as shown in Fig. 2).

Fig. 1 The variation of fixation is stable

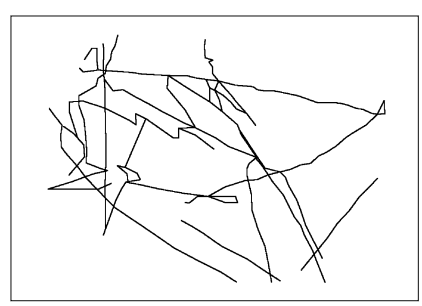

Fig. 2 The variation of fixation is chaotic

The gaze fixation distribution can be shown on a value chart, which is divided into 20 × 20 grids of the same size. The number in each grid represents the frequency that fixation falls on this grid, so each grid has a weight. For example, the number 3 represents the 5 × 5 grids in the central area, 2 represents the grids in the middle square ring, and 1 represents the grids in the outer square ring (as shown in Fig. 3).

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Biography: Lu Jian(1972—), male, doctor, professor, Lujian_1972@seu.edu.cn.

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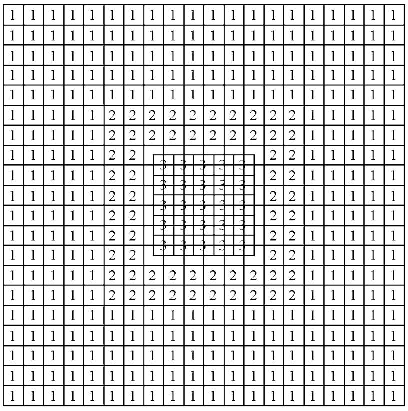

Fig. 3 The weight of gaze fixation distribution

1.2 Fixation duration

Fixation duration reflects a driver's attention degree to some fixed areas. This measurement can be obtained by employing an eye tracker to sample in a fixed frequency. Some related research has illustrated that the mean fixation duration of a typical gaze is approximately from 250 to 300 ms. According to our experiments, the relationship between driver mean fixation duration and the traffic flow at an intersection is shown in Fig. 4.

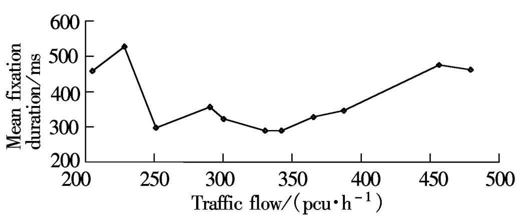

Fig. 4 Relationship between driver mean fixation duration and traffic flow at an intersection

Analyzing the data of our experiments, we find that the variation of a driver's total gaze time T is very small at an intersection. Assuming that the number of gaze fixations is n and the mean fixation duration is $\bar{t}$, then $\bar{t} = T/n$. As n increases, $\bar{t}$ reduces inevitably[4].

1.3 Visual angle distribution

When the traffic flow at an intersection is little, a driver is not so tense and pays more attention to some unimportant traffic information on both sides of his/her vehicle and vehicles in front of him/her, so his/her search scope in the horizontal direction is wide. However, when the traffic flow at an intersection is heavy, the driving task is arduous; the driver is tenser, and his search scope in the horizontal direction is narrow.

Brackstone et al.[5] divided the gaze region into left, ahead, right, up and down in their researches of the driver's visual distribution region on ordinary roads, as shown in Fig. 5.

Because a driver's gaze scope at an intersection may be bigger than that in the ordinary road sections, we define five regions as follows on the basis of Brackstone's idea of division[5] and Victor's region division method[6]. On the horizon, the region that is smaller or equal to $-30°$ is the left region, the region that is bigger or equal to $30°$ is defined as the right region, the $60° \times 30°$ rectangle between $(-30°, -15°)$ and $(30°, 15°)$ is defined as the central region, and the central region is divided into up and down in the vertical direction, as shown in Fig. 6.

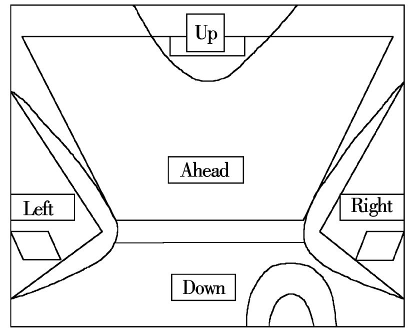

Fig. 5 The gaze region divided by Brackstone

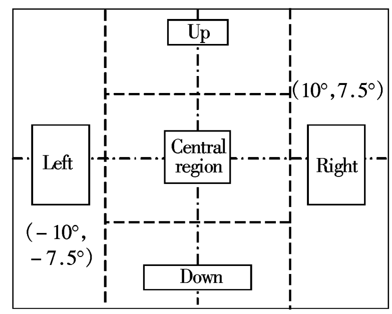

Fig. 6 The gaze region divided by this paper

When the traffic flow is heavy, drivers need to pay more attention to the central and left regions and less to the right region. So we should set different weights for different regions; here, set 1.5 for the left region, 2 for the central region, 1 for the right region. Then the quantitative relationship between the driver's visual angle distribution and the traffic flow at an intersection can be established through the weights, which is as follows:

$$M = 1.5x + 2y + z \tag{1}$$

where x, y, z are the distribution frequency of a driver's visual line falling on the left region, the central region, and the right region, respectively.

1.4 Driver's eye movement test

In order to establish the quantitative relationship between driver dynamic visual characteristic parameters and the traffic flow, we collect the data describing the driver's dynamic visual characteristics in a real road environment. We choose a signal-controlled cross intersection, which has obvious peak hours and off-peak hours, as the testing site. When drivers drive across the intersection under different traffic flow levels, we record the eye movements by an eye tracker data simultaneously, and collect the traffic flows at peak hours and at off-peak hours by the video recording equipment that is installed on this intersection.

2 Correction of Intersection Saturation-Flow-Rate Model

2.1 Relationship between traffic flow and driver's eye movement

The analysis results of the above experiments indicate that when the traffic flow is unsaturated, the change in driver eye movements is relatively stable, but when the traffic flow is saturated, the change in driver eye movements is drastic. The relationship between the traffic flow and a driver's vision stability is shown in Fig. 7.

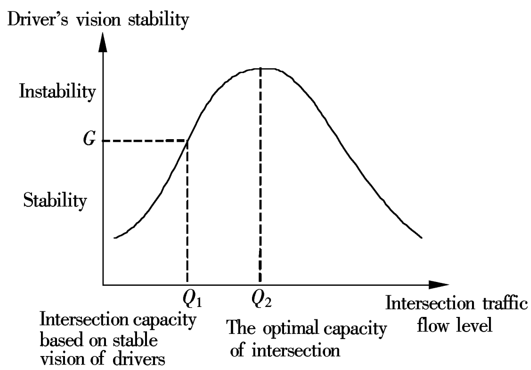

Fig. 7 Relationship between traffic flow and a drivers' vision stability

From Fig. 7, a driver's vision instability point, G, can be determined, and the corresponding traffic flow Q_1, which is also the intersection capacity, can also be determined by the video recording equipment, then G and Q_1 can be fed into the saturation-flow-rate model to calculate the driver correction coefficient.

2.2 Saturation-flow-rate model

The saturation-flow-rate formula is

$$S = S_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{RT} f_{LT} \tag{2}$$

where S_0 is the saturation-flow-rate of lane groups under ideal traffic conditions; the remaining correction coefficients can be obtained from some related manual or measurement on-site.

The driver's correction coefficient is defined as f_d, $f_d \in (0, 1)$. When the traffic flow is small, the driver's factor has almost no effect on saturation-flow-rate, so f_d tends to 1; otherwise, f_d tends to 0. f_d is a function of the driver's dynamic visual characteristics. It mainly includes: 1) Gaze fixation distribution; 2) Mean fixation duration; 3) Visual angle distribution. Denote them as α_1, α_2, α_3, respectively; then $f_d = f(\alpha_1, \alpha_2, \alpha_3)$.

In this paper, the left-turn lane, the through lane and the right-turn lane are analyzed, and the corresponding driver correction coefficients $f_{d\ \text{left-turn}}$, $f_{d\ \text{through}}$, $f_{d\ \text{right-turn}}$ are defined.

2.3 Correction of saturation-flow-rate model

1) Curve fitting of traffic flow

Use Matlab to determine the relationship among α_1, α_2, α_3. Let $S = f(\alpha_1, \alpha_2, \alpha_3)$, and make it best fitting under some kind of criterion.

If the actual traffic flow and the curve fit well, it means that the variation of the driver's dynamic visual characteristics is stable. When the error becomes gradually larger, the driver's dynamic visual characteristics variations are getting unstable, so the unstable point of the driver's dynamic visual characteristics can be determined by curve fitting. The intersection saturated-flow-rate, S, without considering the driver's factor can be determined by the saturated-flow-rate model, and the intersection saturated-flow-rate, S_d, when considering the driver's factor can be determined by curve fitting. Thus, the driver's correction coefficient f_d is

$$f_d = \frac{S_d}{S} \tag{3}$$

2) Correction of saturation-flow-rate model

Collect the drivers' gaze fixation distribution under different traffic flow levels (from off-peak hours to peak hours), and calculate the gaze fixation distribution's weight in each lane. The results are shown in Tab. 1 and Tab. 2.

Collect the driver's fixation duration during the traffic flow from off-peak hours to peak hours at the intersection. The mean fixation duration and the traffic flow in each lane are shown in Tab. 3.

According to the experimental data, a driver's visual angle distribution is calculated under different traffic flow levels at the intersection. The weights of visual angle distribution in each lane are shown in Tab. 4 and Tab. 5.

Tab. 1 Distribution and weight of gaze fixation distribution in the left-turn lane under different traffic flow rates

Frequency of gaze			Weight A	Traffic flow/(pcu·h^{-1})
Central square	Middle square ring	Outer square ring		
0.26	0.66	0.08	2.18	158
0.23	0.70	0.06	2.17	188
0.21	0.67	0.12	2.09	188
0.17	0.65	0.17	2.01	195
0.21	0.67	0.11	2.10	210
0.21	0.73	0.06	2.15	218
0.33	0.59	0.09	2.24	233
0.40	0.51	0.08	2.32	248
0.28	0.61	0.11	2.18	255
0.40	0.57	0.03	2.36	263
0.21	0.71	0.08	2.13	263

Tab. 2 The weight of gaze fixation distribution in the through lane and the right-turn lane under different traffic flow rates

In the through lane		In the right-turn lane	
Weight *A*	Traffic flow/(pcu·h^{-1})	Weight *A*	Traffic flow/(pcu·h^{-1})
2. 36	1 193	2. 16	205
2. 2	1 208	2. 07	228
2. 05	1 223	2. 07	251
2. 02	1 253	2. 25	296
2. 26	1 268	2. 12	296
2. 21	1 275	2. 16	342
2. 24	1 320	2. 04	342
2. 12	1 388	2. 13	365
2. 13	1 388	2. 19	387
2. 08	1 440	2. 15	456
2. 09	1 478	2. 22	479

Note: The traffic flow in the through lane is the sum of those of two through lanes.

Tab. 3 Mean fixation duration at the intersection under different traffic flow rates

In the left-turn lane		In the through lane		In the right-turn lane	
Mean fixation duration/ms	Traffic flow/(pcu·h^{-1})	Mean fixation duration/ms	Traffic flow/(pcu·h^{-1})	Mean fixation duration/ms	Traffic flow/(pcu·h^{-1})
263	158	535	1 193	458	205
299	188	476	1 208	528	228
246	188	335	1 223	298	251
477	195	333	1 253	357	296
335	210	368	1 268	323	296
546	218	300	1 275	290	342
247	233	485	1 320	290	342
222	248	305	1 388	328	365
376	255	420	1 388	346	387
483	263	420	1 440	476	456
509	263	405	1 478	462	479

Note: The traffic flow in the through lane is the sum of those of two through lanes.

Tab. 4 Distribution and weight of visual angle distribution in the left-turn lane under different traffic flow rates

Distribution frequency			Weight *M*	Traffic flow/(pcu·h^{-1})
Left region	Middle region	Right region		
0. 77	0. 05	0. 001	1. 26	158
0. 72	0. 07	0. 003	1. 21	188
0. 72	0. 04	0. 002	1. 15	188
0. 57	0. 06	0. 010	0. 98	195
0. 76	0. 06	0. 006	1. 26	210
0. 71	0. 05	0. 001	1. 17	218
0. 68	0. 09	0. 003	1. 22	233
0. 62	0. 15	0	1. 23	248
0. 69	0. 08	0. 001	1. 18	255
0. 70	0. 14	0. 002	1. 33	263
0. 77	0. 07	0. 000 4	1. 30	263

Tab. 5 The weight of visual angle distribution in the through lane and the right-turn lane under different traffic flow rates

In the through lane		In the right-turn lane	
Weight *M*	Traffic flow/(pcu·h^{-1})	Weight *M*	Traffic flow/(pcu·h^{-1})
1. 31	1 193	1. 22	205
1. 34	1 208	1. 18	228
1. 14	1 223	1. 28	251
1. 28	1 253	1. 39	296
1. 28	1 268	1. 04	296
1. 21	1 275	1. 24	342
1. 2	1 320	1. 34	342
1. 12	1 388	1. 3	365
1. 19	1 388	1. 21	387
1. 09	1 440	1. 26	456
1. 03	1 478	1. 21	479

Note: The traffic flow in the through lane is the sum of those of two through lanes.

From Tab. 1 to Tab. 5, we fit the three main parameters of the drivers' dynamic visual characteristics and the corresponding traffic flow in each lane, and the results are shown in Fig. 8, Fig. 9 and Fig. 10.

From Fig. 8, Fig. 9 and Fig. 10, it can obviously be seen that the traffic flow rate obtained from fitting is lower than that from the saturated-flow-rate model, which indicates that

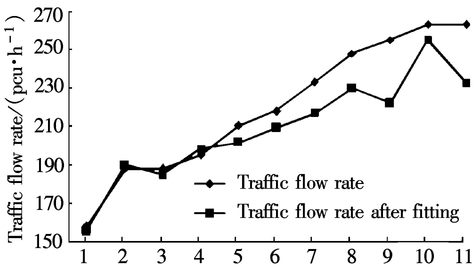

Fig. 8 Traffic flow fitting of the left-turn lane

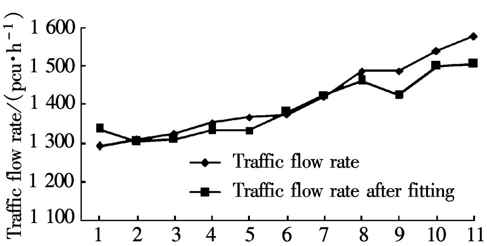

Fig. 9 Traffic flow fitting of the through lane

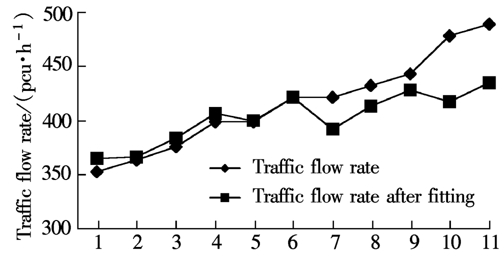

Fig. 10 Traffic flow fitting of the right-turn lane

the driver's factor indeed has some influence on intersection traffic flow. When the traffic flow in the left-turn lane increases to 210 pcu/h, the actual traffic flow begins to deviate from the fitting curve. Similarly, when the traffic flows in the through lane and the right-turn lane increase to 1 388 pcu/h and 342 pcu/h, respectively, the deviation appears again. So, the saturation-flow-rate of each lane can be obtained, as shown in Tab. 6.

Generally, the saturation-flow-rate under an ideal condition is 1 550 pcu/h for the left-turn lane, 1 650 pcu/h for the through lane, and 1 550 pcu/h for the right-turn lane. If the lane width, heavy vehicle and some other correction coefficients[7] are considered, the saturation-flow-rate S in the left-turn lane, the through lane and the right-turn lane are 1 488 pcu/h, 1 410 pcu/h and 1 192 pcu/h, respectively.

According to Eq. (3), the driver correction coefficient in each lane can be obtained, as shown in Tab. 6.

Tab. 6 Driver correction coefficient calculation table

Lane	Actual traffic flow at unstable point of driver's vision/(pcu·h^{-1})	Split	S_d	S	f_d
The left-turn lane	210	24/160	1 400	1 488	0. 941
The through lane	1 388(two lanes)	84/160	1 322	1 410	0. 938
The right-turn lane	342	47/160	1 164	1 192	0. 977

Tab. 6 shows that the influences of the driver's characteristics on the left-turn lane and the through lane are more or less at the same level, but greater than that on the right-turn lane. The reason may be that when the driver is turning left or traveling straight, the region he/she needs to scan is wider than that of when he/she is turning right, since the traffic condition of the former that he/she needs to pay attention to is more complex.

It should be noted that the traffic flow of each lane and the corresponding driver correction coefficient in this paper is just for a specific intersection, and the value may be different for different intersections, that is, of different types, scales or vehicle compositions[8].

2.4 Intersection capacity calculation considering the driver's factor

In this paper, the driver correction coefficient is applied to correct the commonly used intersection capacity model.

First, the capacity of each lane group is calculated. Then, the capacity of each lane group is summed up and the total capacity of the intersection is identified. The capacity of each lane group can be calculated by $C_i = S_i\lambda_i$, where C_i is the capacity of lane group i (pcu/h). S_i is the saturation-flow-rate of lane group i when considering the driver's factor. λ_i is the split, $\lambda_i = (g/T_c)_i$, where g is the green time, T_c is the cycle length. The total capacity is $C = \sum (V_i/S_i)[T_c/(T_c - L)]$, where V_i is the traffic flow rate of lane group i, and L is the total loss in each cycle.

3 Conclusion

In this paper, we analyze the influence of the driver's dynamic visual characteristics on intersection capacity, propose the concept of driver correction coefficient in the saturation-flow-rate model, and study the quantitative relationship between the driver's dynamic visual characteristic parameters and the traffic flow at intersections. We have conducted some experiments on a real intersection to obtain some on-site observations, in order to calculate the driver correction coefficients in each lane at this intersection, and apply them to correct the intersection capacity model.

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基于驾驶员视觉特性的交叉口通行能力研究

陆 建 陈伟伟 范红静

(东南大学江苏省交通运输规划与管理重点实验室,南京 210096)

摘要:为了反映混合交通环境下驾驶员驾驶特性差异对通行能力的影响,根据驾驶员视觉特性提出交叉口通行能力计算中的驾驶员修正系数.采集真实道路环境下的驾驶员视觉特性参数,获取驾驶员在交叉口处注视点分布、平均注视持续时间、视角变化等视觉特性参数,建立交叉口交通流率与驾驶员眼动参数变化关系.分析结果表明,交通流未饱和时,驾驶员眼动参数变化比较平稳,而当交通流率趋于饱和时,眼动参数变化剧烈.根据驾驶员眼动参数变化规律对交叉口通行能力计算的饱和流率模型进行修正,得到考虑驾驶员视觉特性的交叉口通行能力计算方法.

关键词:交叉口;驾驶员视觉特性;饱和流率;通行能力;修正系数

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