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Congestion judgment method at entrances and exits of large-scale parking lots based on average vehicle delay

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Abstract: The significant rise in the number of motor vehicles and the increased utilization of land in China has led to the emergence of numerous large-scale parking facilities, resulting in exacerbated congestion at their entrances and exits. To address this issue, it is essential to first establish criteria for assessing congestion. This study employs an average delay model for various vehicle types and takes into account the distribution ratios of incoming vehicles across different lanes. Through quantitative analysis, the research identifies the causes and severity of congestion for different vehicle categories at parking lot entrances and exits. The findings aim to inform effective management and regulation of traffic flow in these critical areas.

Keywords: traffic engineering; congestion judgement; average vehicle delay; large-scale parking lot

1 Introduction

According to the National Bureau of Statistics, by the end of December 2020, there were 281 million cars in China, of which 244 million were private cars[1]. The proliferation of vehicles and the intensification of land use in the country has given rise to a large number of large-scale parking lots (more than 300 parking spaces) and a series of new parking difficulties, including congestion at entrances and exits. This problem will lead to slow or congested traffic on the connecting roads and the surrounding road network, reducing the efficiency of the roads, and in order to solve this problem, a traffic congestion judgement is needed.

In the past, researchers have done a lot of work to study and judge traffic congestion. Wang Liwei[2] has developed a congestion evaluation model based on a network model and floating vehicle data for congestion identification, and a congestion evaluation model based on principal component analysis. Li Xiaowei[3] has used a simulation approach to develop a model that average delay, average travel time and average queue length were used as traffic status evaluation indicators. Lu Borong[4] selected queue length, average delay and average speed as evaluation indicators through VISSIM simulation. Chang Lijun[5] established a traffic status discrimination method based on (SAGA-FCM)-PNN to improve the recognition accuracy. Yan Yuchan[6] selected average traffic flow speed, traffic flow density and road section saturation as factor indicators to establish a multi-indicator fuzzy comprehensive evaluation model to achieve accurate research and judgement of congestion levels.

In summary, most of the models used for traffic congestion judgement and evaluation are complex and difficult to understand, and their practicality is poor. There are few congestion judgement and evaluation models for parking lots. As for the problem of defining congestion by quantitative indicators, there is no unified standard at home and abroad, and the congestion delay indicators for the entrances and exits of large-scale parking lots have not yet been established.

Therefore, based on the average delay model of various types of vehicles (including arriving vehicles, departing vehicles and road vehicles), this paper innovatively

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uses the average delay of vehicles as a single evaluation index to study and judge the congestion status of entrances and exits of large-scale parking lots. On this basis, this paper introduces the proportion coefficient of the distribution of arrival vehicles on different lanes, and changes the congestion status of entrances and exits by adjusting the proportion coefficient. This will help to accurately determine the degree of influence of the distribution of arriving vehicles on the congestion at the entrances and exits, and provide support for the formulation of strategies to regulate the entrances and exits of large-scale parking lots.

2 Methodology

2.1 Congestion status classification

At present, congestion at the entrances and exits of large-scale parking lots has not been precisely defined. Generally speaking, congestion can be defined from a number of perspectives, including traffic supply and demand and the psychological perception of the traveler. From the perspective of traffic supply and demand, congestion is defined as a period of time when the volume of traffic exceeds the capacity of the road and overflows to form queues[7]. Congestion is manifested by the formation of queues of vehicles and a significant increase in delays[8-10].

Japan uses indicators such as speed and queue length to identify congestion[7]. The US defines traffic conditions as congestion when delays exceed a threshold acceptable to the general public and gives standards for the level of service at unsignalized intersections[8], as shown in Table 1. China uses average delay indicators to evaluate the level of service at signalized intersections and develops a table for the classification of the level of service at signalized intersections[9], as shown in Table 2.

Table 1 Service level standards of unsignalized intersections in the United States

Service level rating	A	B	C	D	E	F
Average delay (s)	≤5	5.1−10.0	10.1−20.0	20.1−30.0	30.1−45.0	>45

This paper defines dynamic and static traffic congestion as the traffic condition when the average delay of a certain type of vehicle exceeds the congestion threshold, taking half of the congestion as the slowdown threshold, and divides various types of vehicle delays into three levels, forming a delay level table, with reference to the level of service standard for unsignalized intersections in the United States and the level of service standard for signalized intersections in China.

Table 2 Service level division of signalized intersections in China

Service level rating	Average delay (s)	Description of the traffic situation
Grade 1	≤15	Smooth flow of traffic with slight resistance
Grade 2	15.1−30.0	Vehicles are running normally with some delays
Grade 3	30.1−50.0	Vehicles can operate normally with large delays
Grade 4	>50	Vehicle congestion and significant delays

The delays experienced by departing vehicles entering the road are greater than the delays experienced by arriving vehicles leaving the main road, so the average delay rating for arriving and departing vehicles in parking lots is as shown in Table 3.

Table 3 Classification of delay levels for arriving and leaving vehicles in parking lots

Delay level	Average delay of leaving vehicle (s)	Average delay of arriving vehicle (s)
Smooth flow	≤25	≤20
Overcrowding	25−50	20−40
Congestion	≥50	≥40

Road vehicles, as vehicles travelling on the main road, have priority and suffer less delay than arriving and departing vehicles in the car park, with the two lanes on the same side suffering more delay than the three lanes on the same side. The average road vehicle delay rating is therefore standardized according to the number of road lanes, as shown in Table 4.

Table 4 Classification of vehicle delay levels on connecting roads

Delay level	Average delay of vehicles on three-lane roads (s)	Average delay of vehicles on two-lane roads (s)
Smooth flow	≤5	≤10
Overcrowding	5−10	10−20
Congestion	≥10	≥20

2.2 Congestion judgement

The flow of the congestion judgement method based on average vehicle delays at the entrances and exits of large-scale parking lots is shown in Figure 1.

1. Select the target large-scale parking lots for the study and conduct an external survey to obtain information on historical traffic volumes and actual vehicle delays for various types of vehicles under different routes.

↓

2. Depending on the type of vehicle, the corresponding vehicle average delay model is selected and the parameters calibrated.

↓

3. Forecast future traffic totals for various road types and analyze how traffic volumes will be composed under different routes.

↓

4. Calculate the average delay range for each type of vehicle and compare it with the average delay threshold for vehicles when congestion occurs.

↓

5. Determine the range of congestion changes for each time period, whether there are adjustable congestion periods, and whether congestion periods overlap.

↓

6. If congestion periods overlap, reallocate congestion periods.

Fig. 1 Flow chart of congestion judgement

2.2.1 Traffic survey

A car park with a total of over 300 parking spaces was selected as the target of the study, and an external survey was carried out to capture video of the traffic flow at the entrances and exits for several consecutive days to obtain historical traffic volumes and actual delay information for various types of vehicles under different paths. This includes the number of vehicles arriving at the car park, the number of vehicles leaving the car park, total road traffic, traffic in the first lane (the lane closest to the entrance/exit), traffic in the second lane (the second road lane from the entrance/exit), the number of vehicles entering the car park in the first lane, the number of vehicles entering the car park in the second lane, the number of vehicles in the first lane affected by vehicles leaving the car park, the number of vehicles in the first lane affected by vehicles in the second lane and the average delay of vehicles, and the average vehicle delay time. The schematic diagram of parking lot access lanes is shown in Figure 2.

2.2.2 Average delay model and parameter calibration

The average vehicle delay model[10] is divided into: an average delay model for arriving vehicles (including entrance gate delays, average delays for vehicles entering the car park in lane 2, average delays for arriving vehicles), an average delay model for departing vehicles (including exit gate delays, delays for vehicles leaving onto the road, average delays for vehicles leaving the car park), an average delay model for road vehicles (including delays for vehicles in lane 1 due to vehicles leaving the car park, first lane vehicle delays due to vehicles crossing in the second lane, average delays for second lane vehicles queuing to enter the car park, average delays for road vehicles).

Before the calibration of the parameters, the observation statistics of the video captured by the survey are firstly conducted, the difference in the number of video frames of each vehicle passing through the start and end

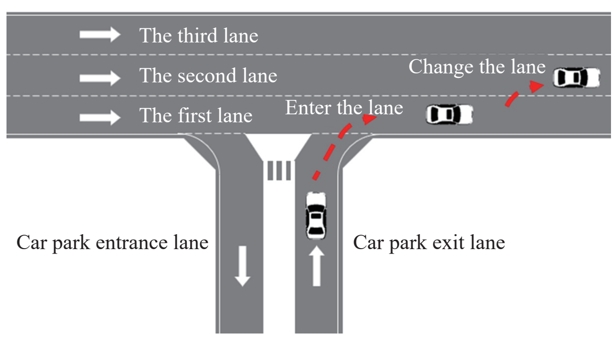

Fig. 2 Schematic diagram of parking lot access lanes

points is recorded, the minimum value of the passing time of all vehicles is the delay-free passing time, the difference between the passing time of other vehicles and the delay-free passing time is the measured delay value of vehicles, the average delay of various types of vehicles in each time interval of the filming period and the traffic volume of different routes are counted and converted into hourly traffic volume. The average delay for each vehicle type and the traffic volume under different paths in each time interval of the shooting period are counted and converted into hourly traffic volume. The average vehicle delay model is then selected according to vehicle type, and the delay model parameters are calibrated using mathematical analysis software based on the average delay values of multiple vehicle types and the traffic volumes under different paths for each vehicle type obtained from the survey observations.

2.2.3 Traffic volume analysis

Obtain the total future traffic volume of each type of road, analyze the way its traffic volume is composed under different paths, convert the traffic volume into hourly traffic volume at an interval of 15 min, and form a statistical table of traffic volume under different paths for various types of vehicles.

2.2.4 Calculation of average delay

Based on the calibrated average vehicle delay model, a scale factor for the distribution of arriving vehicles in different lanes is introduced and the average delay range for each vehicle type is calculated by adjusting the scale factor and compared with the average vehicle delay threshold when congestion occurs, and congestion is judged to occur when the average delay value is greater than or equal to the congestion delay value and not when the average delay value is less than the congestion delay value.

2.2.5 Determine the range of changes in congestion levels

Determine the range of congestion variation for each time period, determine whether there are adjustable congestion periods (if the congestion state is congested regardless of the scaling factor, then there are no adjustable congestion periods, and vice versa), and determine the adjustment strategy based on the scaling factor for the distribution of arriving vehicles in different lanes.

3 Case study

3.1 Jingfeng car park external survey

This paper selects the Jingfeng car park as the object for example analysis. Nanjing Jingfeng car park is located in Nanjing Jiangning District Jingfeng Square, mainly serving the parking demand of Jingfeng Commercial Square, so it is considered to be a commercial car park. There are three levels in the car park, B1, B2 and B3 respectively, with a total of 1 800 parking spaces, and its main entrances and exits are located on the east and west sides of the car park. The east entrance and exit are connected to the two-lane side road of the city main road. The west entrance and exit are connected to the three-lane city side road, which is prone to traffic congestion during peak hours. The east entrance is connected to the two-lane auxiliary road of the main city road. The west entrance is connected to the three-lane city bypass, which is prone to traffic congestion at the entrance and exit during peak hours. The north entrance is for residential vehicles only and is not open to the public, so the east and west entrances are mainly studied.

The camera equipment was selected and set up in accordance with Table 5, and video of the arrival and departure lanes of the car park and the connecting roads was filmed on multiple days, and the survey video was observed and counted.

Table 5 Survey information sheet

Name of car park	Survey method	Date of survey	The moment of investigation
Jingfeng car park	Video shooting Observation statistics	6 January 2021 9 January 2021	15:00−22:00

3.2 Average delay model and parameter calibration

The cases involve three types of vehicles: arriving vehicles, departing vehicles and road vehicles. Based on the difference in the number of lanes on the roads connected to the two entrances, the following models were obtained: average delay model for arriving vehicles at the east entrance/exit, average delay model for departing vehicles at the east entrance/exit car park, average delay model for vehicles on the road at the east entrance/exit, average delay model for arriving vehicles at the west entrance/exit car park, average delay model for departing vehicles at the west entrance/exit car park and average delay model for vehicles on the road at the west entrance/exit, for a total of six models.

Take the example of vehicles arriving at the west entrance, as illustrated in Equation (1).

$$d_{\mathrm{a}}^1=d_{\mathrm{af}}^1+d_{\mathrm{ag}}^1+\frac{q_{\mathrm{a2}}^1}{q_{\mathrm{a}}^i}\times d_{\mathrm{a2c}}^1=d_{\mathrm{af}}^1+\frac{1}{\mu_{\mathrm{a}}^1-q_{\mathrm{a}}^1}\times 3\,600+\frac{q_{\mathrm{a2}}^1}{q_{\mathrm{a}}^1}\times 3\,600\times\frac{1-\mathrm{e}^{-\left\{\left[\left(q_{r1}^1+q_{a1}^1\right)t_{a2c}^1+q_{a2}^1t_{a2f}^1\right]/3\,600\right\}}}{3\,600\times\eta_{\mathrm{a2c}}^1\times\frac{1}{t_{\mathrm{a2f}}^1}\mathrm{e}^{-\left[\left(q_{r1}^1+q_{a1}^1\right)t_{a2c}^1/3\,600\right]}-q_{\mathrm{a2}}^1} \tag{1}$$

where, d_{a}^1 is the average delay in s for vehicles arriving at the west entrance/exit; d_{af}^1 is the fixed delay in s for vehicles arriving at the west entrance/exit; d_{ag}^1 is the average delay of vehicles arriving at the west entrance/exit through the entrance gates, s; q_{a2}^1 is the number of vehicles entering the west entrance/exit in the second lane, in veh/h; q_{a}^1 is the number of vehicles arriving at the west entrance/exit in veh/h; d_{a2c}^1 is the average delay in s of vehicles entering the west entrance/exit in the second lane; μ_{a}^1 is the service rate of the west entrance/exit gates in veh/h; q_{r1}^1 is the traffic volume in veh/h in the first lane of the road near the west entrance/exit; q_{a1}^1 is the number of vehicles entering the west entrance/exit in the first lane, in veh/h; t_{a2c}^1 is the critical gap between the second lane and the vehicles reaching the west entrance/exit, in s; t_{a2f}^1 is the follow time in s for vehicles from the second lane to reach the west entry/exit; η_{a2c}^1 is the capacity correction factor for vehicles in the second lane crossing the first lane into the western entrance/exit.

The parameters were calibrated according to the method described in the previous section and the results are shown in Table 6.

From this, taken into Equation (1), it follows Equation (2).

$$d_{\mathrm{a}}^1=d_{\mathrm{af}}^1+d_{\mathrm{ag}}^1+\frac{q_{\mathrm{a2}}^1}{q_{\mathrm{a}}^i}\times d_{\mathrm{a2c}}^1=3.61+\frac{1}{472.1-q_{\mathrm{a}}^1}\times 3\,600+\frac{q_{\mathrm{a2}}^1}{q_{\mathrm{a}}^1}\times 3\,600\times\frac{1-\mathrm{e}^{-\left\{\left[\left(q_{r1}^1+q_{a1}^1\right)\times 4.84+q_{a2}^1\times 5.36\right]/3\,600\right\}}}{3\,600\times 0.92\times\frac{1}{5.36}\mathrm{e}^{-\left[\left(q_{r1}^1+q_{a1}^1\right)\times 4.84/3\,600\right]}-q_{\mathrm{a2}}^1} \tag{2}$$

Table 6 Calibration results of model parameters for arriving vehicle delay at west entrance/exit

Parameter calibration results					
d_{af}^1	3.61	μ_{a}^1	472.1	t_{a2c}^1	4.84
t_{a2f}^1	5.36	η_{a2c}^1	0.92	-	-
Evaluation of model fit wholeness					
SSE	132.14	-	-	R^2	0.937 9

3.3 Traffic volume analysis

The traffic volumes of arriving and departing vehicles, departing vehicles and road vehicles at each entrance and exit of the car park are predicted by the classical ARMA method[11-12], using MAPE, MAE and RMSE as evaluation indicators to obtain total traffic volumes for all types of vehicles.

For the way in which its traffic volume is composed under different paths, the video analysis shows that the ratio of traffic volume in the first lane of the road near the west entrance/exit to the total traffic volume of the road is stable at 1/3, which can be written as Equation (3).

$$q_{\mathrm{r1}}^1=\frac{1}{3}q_{\mathrm{r}}^1, \tag{3}$$

where q_{r}^1 is the total traffic volume in veh/h on the roads near west entrance/exit.

In addition, for vehicles arriving at the west entrance/exit, the constraint is met:

$$q_{\mathrm{a}}^1=q_{\mathrm{a1}}^1+q_{\mathrm{a2}}^1. \tag{4}$$

Therefore, it is assumed that the self-regulation through traffic flow does not change the total amount of traffic flow on the connecting roadways, i.e. q_{r1}^1 is not affected by the allocation ratio of q_{a1}^1 and q_{a2}^1.

Proportion of vehicles arriving at the car park in the first lane of the west entrance can be defined as:

$$p_{\mathrm{a}}^1=\frac{q_{\mathrm{a1}}^1}{q_{\mathrm{a}}^1}, \tag{5}$$

where p_{a}^1 is the proportion of vehicles arriving at the car park in the first lane of the west entrance/exit.

Then,

$$q_{\mathrm{a1}}^1=p_{\mathrm{a}}^1q_{\mathrm{a}}^1, \tag{6}$$

$$q_{\mathrm{a2}}^1=(1-p_{\mathrm{a}}^1)q_{\mathrm{a}}^1, \tag{7}$$

$$d_{\mathrm{a}}^1 = d_{\mathrm{af}}^1 + d_{\mathrm{ag}}^1 + \frac{q_{\mathrm{a2}}^1}{q_{\mathrm{a}}^i} \times d_{\mathrm{a2c}}^1 =$$

$$3.61 + \frac{1}{472.1 - q_{\mathrm{a}}^1} \times 3\,600 + (1 - p_{\mathrm{a}}^1) \times 3\,600 \times$$

$$\frac{1 - \mathrm{e}^{-\left\{\left[\left(q_{r1}^1 + p_a^1 * q_a^1\right)4.84 + (1-p_a^1)q_a^1 5.36\right]/3\,600\right\}}}{3\,600 \times 0.92 \times \frac{1}{5.36}\mathrm{e}^{-\left[\left(q_{r1}^1 + p_a^1 q_a^1\right)4.84/3\,600\right]} - (1 - p_{\mathrm{a}}^1)q_{\mathrm{a}}^1}. \quad (8)$$

Analysis of the video shows that $0 \leqslant p_{\mathrm{a}}^1 \leqslant 1$.

4 Results and discussion

Based on the predicted values of total traffic for each type of vehicle and the proportionality factor of vehicles arriving at the car park in the first lane, the average delay range for each type of vehicle at each moment is calculated at 15 min intervals and compared with the average delay threshold for vehicles when congestion occurs.

Using the arriving vehicles at west entrance/exit as an example, the calculation results are shown in Table 7, where green indicates smooth flow of traffic, blue indicates overcrowding and yellow indicates congestion.

The results of the average delay determination for arriving vehicles at the western entrance and exit are as follows:

Table 7 Calculation results of average delay range of arriving vehicles at west entrance/exit

Moment	Traffic forecast (veh/h)			Proportion of vehicles arriving at the car park in the first lane at the west entrance/exit p_a^1										
	q_a^1	q_r^1	q_{r1}^1	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1	130	900	300	19.9	19.2	18.5	17.9	17.3	16.7	16.1	15.6	15.1	14.6	14.1
2	180	900	300	23.5	22.5	21.6	20.7	19.9	19.1	18.4	17.7	17.1	16.5	15.9
3	200	1 200	400	29.5	27.5	25.8	24.2	22.8	21.5	20.4	19.4	18.4	17.6	16.8
4	220	1 400	467	38.1	34.2	31.0	28.3	26.1	24.2	22.5	21.1	19.9	18.8	17.9
5	300	1 200	400	61.6	50.9	43.8	38.8	35.1	32.2	30.0	28.2	26.7	25.5	24.5
6	300	1 300	433	75.7	58.3	48.0	41.3	36.6	33.2	30.6	28.5	26.9	25.6	24.5
7	300	1 450	483	129.7	78.3	57.6	46.5	39.6	34.9	31.6	29.1	27.2	25.7	24.5
8	450	1 450	483	145.8	143.1	138.1	126.5	72.1	262.8	189.9	176.7	171.3	168.3	166.5

At moment 1, at current traffic volumes, all vehicles arriving at the west entrance/exit are in the state of smooth flow, regardless of the proportion of vehicles arriving at the car park in lane 1 and lane 2.

At moments 2, 3 and 4, with the current traffic volumes, the vehicles arriving at the west entrance/exit will be in the smooth flow or overcrowding, influenced by the proportion of arriving vehicles in lane 1 and lane 2.

At moments 5, 6 and 7, congestion will occur at the vehicles arriving at the west entrance/exit at the current traffic volumes, but when the ratio of vehicles arriving at the car park in lane 1 to those arriving in lane 2 is adjusted, the congestion can be changed to overcrowding.

At moment 8, with the current traffic volume, the west entrance/exit is congested. Adjusting the ratio of vehicles arriving at the car park in lane 1 to those arriving in lane 2 cannot change the congestion, so it is necessary to carry out a linkage adjustment of the traffic volume from the multiple entrances and exits to the car park.

In summary, at moments 2, 3, 4, 5, 6 and 7, by adjusting the proportion of vehicles arriving at the car park in lane 1, the average delay can be effectively reduced and the congestion situation improved at the same time, while at moments 1 and 8, although the congestion situation is not changed, there is still a proportional factor that makes the average delay the shortest. In practical application, this can be used as a reference to effectively control the proportion of vehicles arriving at the car park in the first lane through induction to reduce the average delay of vehicles, thus improving the traffic congestion.

5 Conclusions

In this paper, we propose a congestion judgement method based on the average delay of vehicles at the entrances and exits of large-scale parking lots. This paper innovatively uses the average delay of vehicles as a single evaluation index. Based on the quantitative analysis of the causes of congestion and the degree of congestion of each type of vehicles, this paper introduces the proportion coefficient of the distribution of arriving vehicles on different lanes into the delay model, and changes the congestion state of entrances and exits by adjusting the proportion coefficient. The lane level induction of vehicles arriving at the car park has a realistic guiding effect, but no in-depth study has been conducted on the specific induction measures and multiple entrances/exits linkage adjustment measures, which can be followed by universal induction adjustment measures for different delay ranges.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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