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INTELLIGENT OPENING OPTIMIZATION ALGORITHM OF EXPRESSWAY TOLL CHANNEL BASED ON LANE CONTROL

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Abstract

In order to solve the problem of poor matching effect between traffic demand and capacity at the entrance and exit of toll stations and alleviate traffic congestion caused by tidal traffic demand, a concept of lane control was introduced into toll station management, and an intelligent opening optimization method of toll plaza channels is proposed in this paper. The function of Manual Toll Collection (MTC)/Electronic Toll Collection (ETC) mixed lane and the charging direction of ETC lane are dynamically adjusted in the method to improve the traffic efficiency of toll plaza. Aiming at minimizing the average waiting time of all vehicles at the entrance and exit of the toll station, and considering the constraints such as lane division, lane function and traffic intensity, an optimization model of toll plaza channel opening is established. By comparing the optimization control scheme and the traditional control scheme of ETC lane with non-switching charge direction, the results show that under the two traffic schemes where the entrance and exit traffic demand and the number of entrance and exit lanes do not match, the lane control scheme can reduce the average waiting time by 40.21% and 51.86%, respectively, and improve the traffic efficiency of the toll plaza effectively.

Key Words

Traffic engineering, lane control, optimal opening number of toll station channels, toll plaza, expressway

1. Introduction

In order to build the operation and management mechanism of "one network" of national expressways and improve the service quality of expressways, 487 provincial toll stations in 29 networked provinces in China were basically canceled by the end of 2019, and the promotion and application of electronic toll collection was gradually accelerated. The Implementation Suggestions for the Cancellation of Provincial Toll Stations on Expressways requires that "realize the full coverage of the ETC system functions of all toll gates entrance and exit lanes, and only reserve one mixed lane to handle traffic special conditions." This "one-size-fits-all" lane reconstruction scheme and the lower than expected ETC utilization rate have resulted in queue congestion at some toll stations. For example, in May 2020, 434 toll stations in China had congestion of more than 500 m [1]; at the same time, traffic congestion will lead to aggravation of environmental pollution [2]. Therefore, reasonable configuration schemes of ETC lane and mixed lane in ETC promotion transition toll plaza are discussed to improve the operation efficiency of toll plaza. Aiming at construction and operation cost and delay cost, Jiyang Beibei et al. discussed the lane layout scheme of toll plaza under different flow composition and ETC vehicle proportion [3]. Considering the diversification of charging methods, such as cash payment, mobile payment and card swiping payment, Yang Tao et al. established the service time calculation model with diversified charging methods and then gave the optimal layout scheme of lanes in toll plaza [4]. Taking toll station operation cost and user delay cost as goal, and combined with queuing theory, Lin Peiqun et al. established the optimization model of toll station lane setting [5].

The above researches discuss the setting of toll plaza lanes during the construction period, and the operation period should focus on how to balance the operating cost of the toll station and the user cost to minimize the system cost [6]. Taking the operating cost of the toll station, users' fuel consumption cost and time cost as the goals, Cui Hongjun et al. established the best lane opening quantity model with the least total cost [7]. Neuhold et al. developed the Lane Allocation Optimization Algorithm of toll plaza based on the traffic state detection system of toll station camera and guided vehicles to the area with short queue length [8]. Jiyang Beibei et al. dynamically adjusted the number of lane openings in toll stations based on traffic volume and established an optimization model for lane openings in toll plazas considering user balance [9]. From the perspective of customer satisfaction, Li et al. studied the reasonable open number of toll lanes [10]. In

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order to alleviate the congestion of toll station, improve the operation efficiency and make the lane setting of toll station more reasonable, researches on the calculation method of toll station capacity [11, 12], mixed lane capacity [13], toll plaza capacity under different toll booth layout [14], toll station queuing behaviour [15, 16] and toll station traffic flow prediction [8] have been carried out.

In order to improve the traffic capacity of toll plaza during peak hours, many toll stations set up compound lanes to alleviate traffic congestion [17]. However, this partial transformation mode of the toll station traffic capacity improvement is limited. Due to the limitation of land area, it is also difficult to expand the toll plaza (physical expansion). Therefore, using the dynamic control method based on lane control of urban intersections for reference, the two-way traffic demand is balanced by adjusting dynamically the number of import and exit lanes [18, 19]. For example, setting up a tidal toll lane is in the toll plaza [20], this way of lane layout has been built on a pilot basis in the Fushan main line toll station of G15 Shenhai expressway, and the practical application effect is optimal. In addition, according to the requirements of the Overall Technical Scheme for Canceling Provincial Toll Stations of Expressways, "Long-term benchmarking of free-flow tolling models in developed countries, and finally realization of open free-flow tolling on expressways in China," as well as the launch of a new generation of smart transportation technology such as smart remote-controlling mobile guardrails, autopilot [21, 22], make the change of toll plaza lane toll direction and the central separation belt isolation guardrail position switch be fast, convenient and intelligent, all of these provide technical support for lane dynamic control of toll plaza.

Therefore, this paper introduces the concept of lane control at urban intersections into toll stations and establishes an intelligent opening optimization model of toll plaza channels based on lane control. The research aiming at improving the traffic capacity of toll station through the dynamic division of lane functions and directions, and alleviating the congestion of toll station caused by the tide phenomenon of traffic demand, and realizing the "intelligent capacity expansion" of the toll station.

2. Concept of Toll Plaza Channel Opening Based on Lane Control

The general layout of lanes in the toll plaza is shown in Fig. 1. ETC lane is usually set on the leftmost side of the driving direction. The charging direction of ETC lanes can be changed quickly, and it is close to the central separation belt to facilitate lane switching. Thus, this article only considers the dynamic adjustment of lane directions for ETC lanes. The function of MTC/ETC mixed lane is dynamically adjusted to meet the traffic demand of different ETC utilization rates. For example, when the exit traffic of a toll station is large, some mixed lanes are set as the MTC toll pattern to meet the traffic demand of the MTC lanes. Meanwhile, the ETC lane direction is adjusted to meet the traffic demand of the ETC lanes, so as to achieve the best traffic efficiency of the

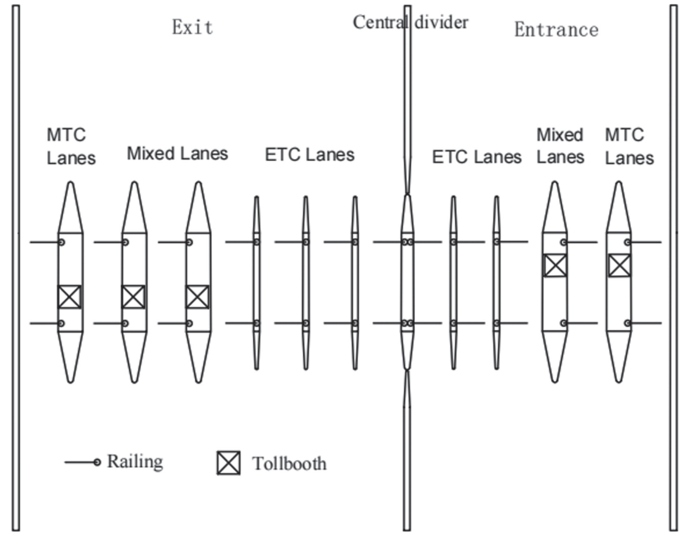

Figure 1. Conventional opening mode of toll plaza channel.

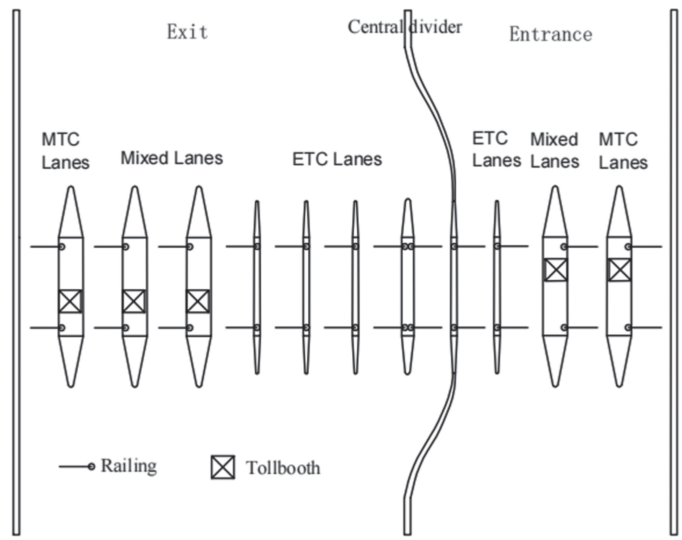

Figure 2. Toll plaza channel opening mode 1.

toll station, as shown in Fig. 2. When the traffic flow at the entrance of the toll station is large, more ETC lanes are allocated as the entrance lanes. At the same time, the function of MTC/ETC mixed lane is adjusted to balance the traffic demand of ETC lanes and MTC lanes at the entrance and exit, as shown in Fig. 3. Therefore, the toll plaza channel opening method based on lane control can reasonably and effectively regulate the toll lane type and direction to alleviate the one-way congestion. It can also provide a theoretical basis for the solution of the tidal congestion problem at the expressway toll station.

3. Optimization Model

3.1 Objective Function

When the conventional layout of the entrance and exit of the toll station can meet the traffic demand, it is meaningless to dynamically divide the lane function and direction. Therefore, the channel opening optimization

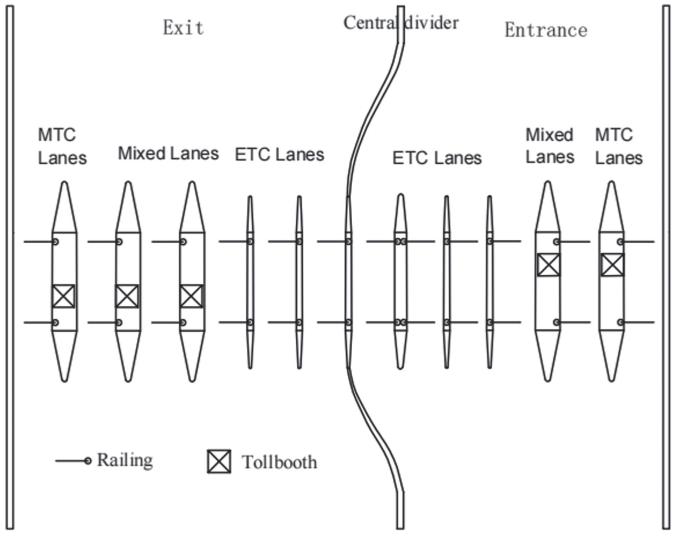

Figure 3. Toll plaza channel opening mode 2.

method of toll plaza based on lane control is applicable to the period of congestion caused by toll station traffic, and some provinces have issued congestion-free express traffic policies and documents. When the toll station is congested to a certain extent, it needs to lift the pole for free. Therefore, when the toll station is congested, the operation management pays more attention to the traffic efficiency. This paper takes the average waiting time of all vehicles at the entrance and exit of the toll station as the target:

$$\min \frac{\sum_{\forall i}\sum_{\forall j}\lambda_{ij}d_{ij}}{\sum_{\forall i}\sum_{\forall j}\lambda_{ij}} \tag{1}$$

where λ_{ij} is the average arrival rate of vehicles in lane j in direction i, veh·s^{-1}; d_{ij} is the average waiting time in the queue of Lane j in direction i, s; i is the entrance and exit direction of the toll plaza, and $i \in \{\mathrm{c}, \mathrm{r}\}$ is the exit and entrance, respectively; j is the toll lane, and $j \in \{\mathrm{MTC}, \mathrm{ETC}\}$ is MTC lane and ETC lane, respectively.

The process of vehicles queuing to collect cards at the entrance or paying fees at the exit of the toll station can be described by the queuing system model in mathematical statistics. With reference to Expressway Toll Station and Toll Plaza Design Specification (Approval Version), the model is as follows:

$$\rho_{ij} = \lambda_{ij}/\mu_{ij}, \forall i, \forall j \tag{2}$$

$$P_{ij}(0) = \frac{1}{\sum_{k=0}^{x_{ij}-1}\frac{\rho_{ij}^{k}}{k!} + \frac{\rho_{ij}^{x_{ij}}}{x_{ij}!\cdot(1-\rho_{ij}/x_{ij})}}, \forall i, \forall j \tag{3}$$

$$\bar{n}_{ij} = \rho_{ij} + \frac{\rho_{ij}^{x_{ij}+1}}{x_{ij}!\cdot x_{ij}}\frac{P_{ij}(0)}{(1-\rho_{ij}/x_{ij})^2}, \forall i, \forall j \tag{4}$$

$$\bar{q}_{ij} = \bar{n}_{ij} - \rho_{ij}, \forall i, \forall j \tag{5}$$

$$m_{ij} = \frac{\bar{q}_{ij}}{x_{ij}}, \forall i, \forall j \tag{6}$$

$$d_{ij} = \frac{\bar{q}_{ij}}{\lambda_{ij}}, \forall i, \forall j \tag{7}$$

where $\mu_{ij}$is the average service rate of lane j in direction i, veh·s^{-1}; ρ_{ij} is the service intensity of lane j in direction i; x_{ij} is the number of lane j in direction i; $P_{ij}(0)$ is the probability of no vehicle of lane j in direction i; $\bar{n}_{ij}$ is the average number of waiting vehicles of lane j in direction i, veh; $\bar{q}_{ij}$ is the average number of waiting vehicles in the queue of lane j in direction i, veh; m_{ij} is the number of waiting vehicles in each lane of j in direction i, veh; and d_{ij} is the average waiting time of vehicles in lane j in direction B, s.

3.2 Constraint Condition

The sum of all lanes open to the toll plaza shall not exceed the total lanes at the entrance and exit (8). The number of open exit MTC lanes shall not exceed the sum of exit MTC lanes and mixed lanes (9). The number of open exit ETC lanes shall not exceed the sum of exit ETC lanes and mixed lanes (10). The number of open exit lanes cannot exceed the total number of exit lanes (11). The number of open entrance ETC lanes shall not exceed the sum of entrance ETC lanes and mixed lanes (12). The number of open entrance MTC lanes cannot exceed the sum of the entrance MTC lanes and mixed lanes (13). The number of open entrance lanes cannot exceed the total entrance lanes (14). The number of ETC lanes at the entrance and exit should be equal to the total ETC lanes in the toll plaza (15). All types of lanes at the entrance and exit should be equal to the total lanes at the entrance and exit (16):

$$\sum_{\forall i}\sum_{\forall j} x_{ij} \le N_{\max} \tag{8}$$

$$x_{\mathrm{c,MTC}} \le N_{\mathrm{cM}} + N_{\mathrm{cME}} \tag{9}$$

$$x_{\mathrm{c,ETC}} \le y_{\mathrm{c}} + N_{\mathrm{cME}} \tag{10}$$

$$\sum_{\forall j} x_{\mathrm{cj}} \le N_{\mathrm{cM}} + N_{\mathrm{cME}} + y_{\mathrm{c}} \tag{11}$$

$$x_{\mathrm{r,ETC}} \le y_{\mathrm{r}} + N_{\mathrm{rME}} \tag{12}$$

$$x_{\mathrm{r,MTC}} \le N_{\mathrm{rM}} + N_{\mathrm{rME}} \tag{13}$$

$$\sum_{\forall j} x_{\mathrm{rj}} \le N_{\mathrm{rM}} + N_{\mathrm{rME}} + y_{\mathrm{r}} \tag{14}$$

$$\sum_{\forall i} y_i = N_{\mathrm{E}} \tag{15}$$

$$N_{\mathrm{cM}} + N_{\mathrm{cME}} + N_{\mathrm{E}} + N_{\mathrm{rME}} + N_{\mathrm{rM}} = N_{\max} \tag{16}$$

where $N_{\max}$ is the total channels in the toll plaza, N_{cM} is the MTC lanes at the exit of the toll plaza, N_{cME} is the MTC/ETC lanes at the exit of the toll plaza, N_{E} is th ETC lanes in the toll plaza, N_{rME} is the MTC/ETC lanes at the entrance of the toll plaza, N_{rM} is the MTC lanes at the entrance of the toll plaza, andy_i is the lanes in the ETC lane of the toll plaza in direction i.

The traffic intensity of each lane should be less than 1:

$$\frac{\rho_{ij}}{x_{ij}} < 1, \forall i, \forall j \tag{17}$$

In order to avoid excessively sacrificing the traffic efficiency of certain types of lanes, the system traffic efficiency is optimized. The waiting vehicles in each lane and the

Table 1
Traffic Volume at Entrance and Exit

Flow Scheme	Traffic Volume at the Exit/(veh/h)	ETC Utilization rate of Vehicles at the Exit /%	Traffic Volume at the Entrance/(veh/h)	ETC Utilization rate of Vehicles at the Entrance/%
1	3000	90	2900	90
2	3000	80	2900	80
3	3800	90	2200	90
4	2400	90	3500	90
5	4800	90	1200	90
6	1400	90	4500	90

Table 2
Lane Opening Optimization Results

Flow Scheme	Control Scheme	$x_{\mathrm{c,MTC}}$	$x_{\mathrm{c,ETC}}$	$x_{\mathrm{r,MTC}}$	$x_{\mathrm{r,ETC}}$	y_{c}	y_{r}
1	Traditional scheme	2	5	1	4	4	3
	Scheme in this paper	2	5	1	4	4	3
2	Traditional scheme	3	4	2	3	4	3
	Scheme in this paper	3	4	2	3	4	3
3	Traditional scheme	2	5	1	4	4	3
	Scheme in this paper	3	5	1	3	5	2
4	Traditional scheme	3	4	1	4	4	3
	Scheme in this paper	2	3	2	5	2	5
5	Traditional scheme	No feasible solution					
	Scheme in this paper	3	6	1	2	6	1
6	Traditional scheme	No feasible solution					
	Scheme in this paper	1	3	2	6	1	6

average waiting time of vehicles should have a maximum limit:

$$m_{ij} \leq m_{\max}, \forall i, \forall j \tag{18}$$
$$d_{ij} \leq d_{\max}, \forall i, \forall j \tag{19}$$

where $m_{\max}$ is the maximum number of waiting vehicles per channel/veh and $d_{\max}$ is the upper limit value of the average waiting time of the vehicle in the system/s.

The value range constraints of variables are as follows:

$$x_{ij} \geq 1, \forall i, \forall j \tag{20}$$
$$y_i \geq 0, \forall i \tag{21}$$

4. Case Analysis

4.1 Basic Parameters

Taking the toll plaza shown in Fig. 1 as the research object, there are 12 lanes at the entrance and exit of the toll plaza, including 1 MTC lane and 2 mixed lanes at exit, 7 ETC lanes, 1 mixed lane and 1 MTC lane at entrance. Referring to Specification for Design of Expressway Toll Station and Toll plaza, the average service time of exit MTC lane is 16 s, ETC lane is 4 s and entrance MTC lane is 8 s. In order to verify the application effect of toll plaza channel opening method based on lane control, another control scheme of ETC lane with unswitching charge direction (hereinafter referred to as "traditional scheme") is considered, and the two control schemes are compared and analysed. The composition of traffic flow and volume at the entrance and exit are shown in Table 1. According to the optimization model in this paper, it is solved by MATLAB programming, and the results are shown in Table 2.

4.2 Result Analysis

The VISSIM micro-simulation software was used for comparative analysis of the two control schemes. The service rates of various toll lanes in VISSIM were corrected to the basic parameters given in Section 3.1, and the random

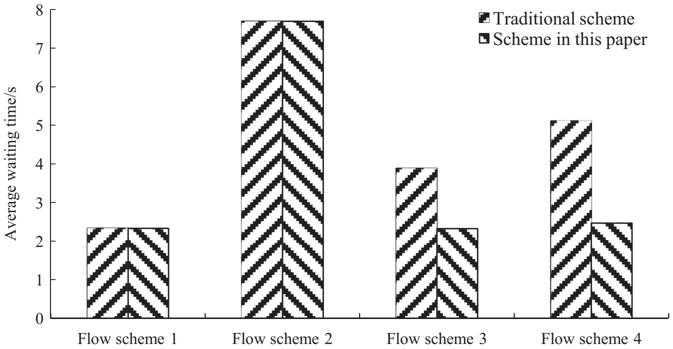

Figure 4. Comparison and analysis of average waiting time.

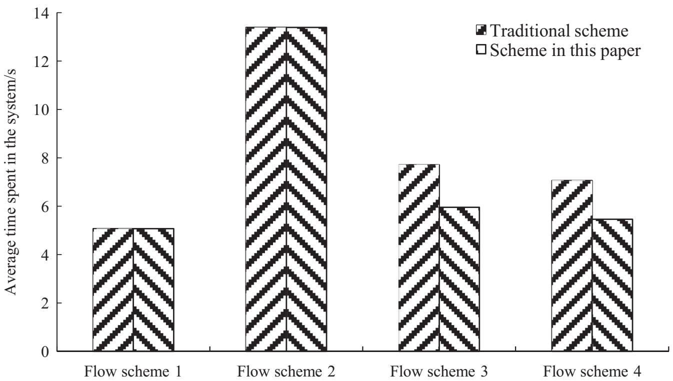

Figure 5. Results of VISSIM, comparative analysis of average consumption time in the system.

seed was adjusted for 10 times to take the mean value as the evaluation parameter. The simulation results are shown in Fig. 5 and Table 3. Under the same traffic input, there are great differences in the traffic efficiency of toll stations due to different ETC utilization rates. For example, the total average waiting time of flow scheme 1 is only 2.33 s, while the total average waiting time of flow scheme 2 reaches 7.69 s. Therefore, ETC promoting can significantly improve the traffic efficiency of toll stations. Meanwhile, different ETC utilization rates will also lead to different functions of entrance and exit lanes. For example, there are two MTC lanes opened under flow scheme 1, while under flow scheme 2 three MTC lanes were opened. Under flow scheme 3, because the exit traffic demand is significantly higher than the entrance traffic demand, the control scheme proposed in this paper allocates more ETC lanes for exit vehicles. By dynamically adjusting the lane direction and lane function, the problem of mismatch between the exit traffic demand and the number of lanes is solved. Compared with the traditional scheme, the proposed scheme can reduce the total average waiting time by 40.21%. Flow scheme 4 is just opposite to flow scheme 3, where the traffic demand at the entrance is significantly higher than that at the exit, so more ETC lanes need to be allocated for entrance lane. Compared with the traditional scheme, the total average waiting time is reduced by 51.86%. If the gap of the flow at the entrance and exit of the toll station continues to increase, such as in flow scheme 5 and flow scheme 6, there is no

Table 3
Comparison of Evaluation Indexes of Optimization Results

		Average Waiting Time/s						Results of VISSIM	
Flow Scheme	Control Scheme	Exit MTC	Exit ETC	Entrance ETC	Entrance MTC	Waiting Wtime/s	Decline Rate of Total Average Waiting Time/%	Average Elapsed Time/s	Drop Rate of Average Elapsed Time/%
1	Traditional scheme	12.80	0.47	14.50	1.70	2.33	—	5.07	—
	Scheme in this paper	12.80	0.47	14.50	1.70	2.33	0	5.07	0
2	Traditional scheme	38.28	1.14	5.68	7.07	7.69	—	13.39	—
	Scheme in this paper	38.28	1.14	5.68	7.07	7.69	0	13.39	0
3	Traditional scheme	39.77	1.60	7.65	0.50	3.88	—	7.71	—
	Scheme in this paper	3.77	1.60	7.65	2.71	2.32	40.21	5.96	22.70
4	Traditional scheme	0.88	0.72	28.00	5.90	5.11	—	7.06	—
	Scheme in this paper	6.36	4.31	1.43	1.01	2.46	51.86	5.46	22.66
5	Traditional scheme	—							
	Scheme in this paper	9.39	1.73	2.91	2.25	2.46	—	7.49	—
6	Traditional scheme	—							
	Scheme in this paper	26.35	0.51	2.67	1.12	1.71	—	4.96	—

feasible solution for the traditional scheme, indicating that the scheme in this paper can well solve the problem of poor matching effect between the traffic demand and capacity of the entrance and exit of the toll station caused by tidal phenomenon.

5. Conclusion

The main conclusions of this research were as follows:

(1) Aiming at the congestion problem of toll station caused by the tide phenomenon of expressway traffic demand, and drawing lessons from the lane-based dynamic control method of urban intersection, this paper puts forward the lane control-based channel opening optimization method of toll plaza. It can dynamically adjust the function and direction of toll lane to match the traffic demand at the entrance and exit and realize the "intelligent capacity expansion" of toll station.

(2) In order to optimize the traffic efficiency system of toll plaza, taking the average waiting time of all vehicles at the entrance and exit of toll station as the target, combined with queuing theory and considering the constraints such as lane division, lane function and traffic intensity, an optimization model of toll plaza channel opening based on lane control is established.

(3) Through case analysis, it is found that the higher the utilization rate of vehicle ETC, the better the traffic efficiency of toll plaza. When the traffic demand at the entrance and exit does not match the number of lanes at the entrance and exit, the lane-based control scheme will help to improve the traffic efficiency of the toll plaza. Compared with the traditional scheme, the total average waiting time under traffic scheme 3 and traffic scheme is reduced by 40.21% and 51.86%, respectively.

(4) In the follow-up study of this paper, we should pay more attention to the optimization scheme of lane control channel opening under different lane layout types of toll plaza, such as MTC on the left side of driving direction, ETC and MTC randomly combined on the left side of driving direction. Meanwhile, it is also necessary to discuss the impact of open mixed lane charging on lane control.

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