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An environment-friendly control method for congestion flow ahead of expressway toll stations

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Abstract: To alleviate the resulting increase in energy consumption and emissions and other issues caused by the traffic congestion ahead of the expressway toll station, a novel traffic flow control method is put forward based on the environment-friendly conception. The technical thinking of inducing the slowly moving traffic into a batch pass is determined based on the conclusion of the research, traffic flow theory and traffic sensing detection technology. The model of stop times is established and the parameters of the system are optimized in accordance with the principle of minimizing the fuel consumption. The optimal location selection of traffic control lights and Detector 2 for queue of different lengths at toll stations are calculated based on the model. Finally, the effect of the congestion flow control system is verified via the Paramics simulation system. The result shows that the control system is capable of reducing 90% of fuel consumption for vehicles going through toll stations.

Key words: traffic engineering; traffic congestion; traffic flow theory; toll station; fuel consumption

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Due to adverse weather, traffic accidents, traffic demand fluctuations and other factors, the areas at expressway toll stations, which are called traffic bottlenecks of the expressway, always suffer from long queues. Frequent start and stop and long-time engine idling in traffic congestion lead to a dramatic increase in fuel consumption and emissions, severely undermining people's health. According to statistics, the fuel consumption of 3 min of engine idling is sufficient for 1 km of normal driving, and the fuel consumption of start is 3 to 6 times as much as that of normal driving. The fuel consumption of vehicles moving slowly through toll stations is 16 to 20 times as much as that of normal driving.

Much research on traffic congestion at highway toll stations has been done in many countries. For example, the conclusion is drawn that when the traffic bottleneck is congested, the phenomenon of road capacity drop will occur and the dissipation flow will be 10% to 30% less than the capacity of the traffic bottleneck[1-2]. Based on the three cellular automaton model for mixing traffic (NaSch, VDR and BL), stop times and start fuel consumption in unit time were studied[3]. Based on the vehicle recognition system and the mutual relationship between vehicle position, a congestion detection method without consideration of traffic control was put forward[4].

Secondly, there is plenty of research on the calculation method of fuel consumption, which are categorized as the theoretical fuel consumption model, multiple regression model and fuel consumption model based on engine experiments. For example, the Brazilian fuel consumption model, a statistical fuel consumption model, was established by using the regression analysis method to relate the unit fuel consumption to the engine power and the calibration speed. TRL, a British institute for transport studies, compared and analyzed the results of engine experiments, and the experimental fuel consumption model was established. Biggs[5] used a similar modeling technology to build the ARFCOM fuel consumption model, which laid the foundation of the HDM-4 fuel consumption model. Smit et al. [6] studied the fuel consumption in different speed, delay and congestion conditions, respectively, and the fuel consumption models influenced by different factors were established.

Developed western countries have made progress in controlling vehicle flow by doing research on the highway ramps. In 1965, Wattleworth et al. [7] were the first who considered controlling the traffic by using the highway ramps. In 1975, Masher et al. [8] built a model that can obtain the rates of ramp control adjustment by means of analyzing the relationship between the road capacity and the traffic demand. Papageorgiou et al. [9] separated the road section, and then succeeded in changing the static model to the dynamic model. Taylor et al. [10] achieved the results in controlling traffic via using the ramp. Smulders[11], who was the representative of the territory, studied the application of variable speeds and provided a guideline for achieving control of the main roads.

Based on the model of stop times, the traffic flow theory and the traffic sensing detection technology, traffic control technology is put forward in this paper. It is of

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great significance to energy conservation and emission reduction of expressways, because it can dramatically reduce start and idle fuel consumption without increasing the passing time of vehicles.

1 Current Toll Station Types and Applicable Conditions of the Traffic Control Technology

The current toll stations in our country can be classified into main line toll stations and ramp toll stations. The layout types of main line toll station includes: a two-way dislocation charge, that is two toll plazas are staggered over 120 m or more along the center line to form two individual toll stations (commonly used), one-way charge (commonly used) and alternate station staggered charge (uncommonly used). The layout types of ramp toll station includes: centralized type (commonly used) and decentralized type (uncommonly used).

The traffic control technology at the toll station proposed in this paper aims at the charging process of one-way traffic flow, so it can be applied to all toll station layout types except for the alternate station staggered charge type. When the economic benefit of laying the system is greater than the cost, this system should be introduced.

2 Characteristics of Traffic Congestion at Toll Stations

The traffic congestion at toll stations can be demonstrated in two states, as shown in Tab. 1.

Tab. 1 Long-time stagnation and slowly moving traffic

Congestion state	Reasons
Long-time stagnation	The complete close of expressways is due to traffic accidents or severe weather conditions.
Slowly moving traffic	Some lane sections are closed due to road construction or traffic accidents; the traffic far exceeds the traffic capacity of toll stations on special days (such as holidays) due to a sharp increase in traffic.

Under the state of long-time stagnation, vehicles always park with stopped engines, so that the restart of engines may influence traffic efficiency, and the air pollution caused by frequent start and stop can be much more than at normal times[12-13]. The analysis shows that, under the state of slowly moving traffic, most vehicles are in a car-following driving model with frequent starts and stops, and the start and idle fuel consumption dramatically increases.

3 Principle of Traffic Control System

The design principle of the traffic control system is to manage and control traffic without increasing passing time and to change the slowly moving traffic into a batch pass so as to significantly reduce idle time and vehicle braking times and control traffic by setting signal lights at a certain distance from toll stations. The structure and control flowchart of the congestion flow control system at expressway toll stations are illustrated in Fig. 1, where a is the length of vehicle square; L_1 is the distance between the traffic control lights and the widened section; L_2 is the distance between Detector 2 and toll stations, of which the endpoint near the toll station is located at the alignment place of driving cab and toll booth window; x is the queue length in the upper reach of the lights when control lights change from red to green when they are operating properly.

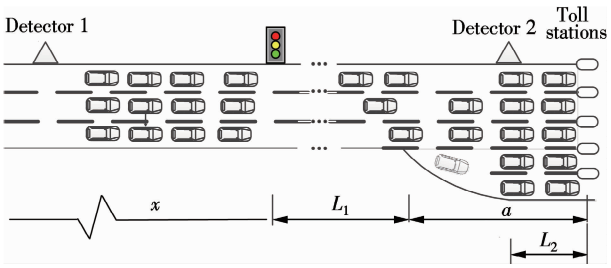

Fig. 1 Control system structure and facilities layout

It is noteworthy that x can be obtained via the detecting analysis of the image[14]. All the entrances of the toll stations in the model are working charging channels, the diverging of traffic flow caused by part of the charging channels' closing have no impact on the operation of the system.

When the vehicle queue at toll stations reaches Detector 1, the traffic control system is on and the traffic control lights turn red to shut off the traffic. The vehicle queue in the lower reach of the traffic control lights is detected by Detector 2. When the queue is shortened to Detector 2, the traffic control lights turn green, and the vehicles of the upper reach are released. When the new queue of the released vehicles at the toll stations reaches Detector 1, the traffic control lights turn red, and the vehicles are cut off after the traffic control lights. When the new queue of the released vehicles at toll stations does not reach Detector 1, the traffic control system stops.

The traffic control system changes the slowly moving traffic into a batch pass without increasing passing time; drivers may stop engines according to traffic control lights to avoid idling, frequently starting and braking in congested traffic.

4 Determination of Flow Control System Parameters

According to the control system structure and facilities layout, there are three specific parameters involved in the system, which, respectively, is the position of Detector 1, the position of Detector 2 and the position of traffic control lights. The position of Detector 2 determines the optimal time point to release the vehicles in the lower reach of traffic control lights; Detector 1 is only used to start or shut down the traffic control system, and its position can be set in accordance with the needs of different toll stations.

4.1 Model of stop times

The model of stop times is established to analyze the effect of the system. According to the principle of the system, the passing process of vehicles from queuing to passing through toll stations can be divided into two parts (see Fig. 2).

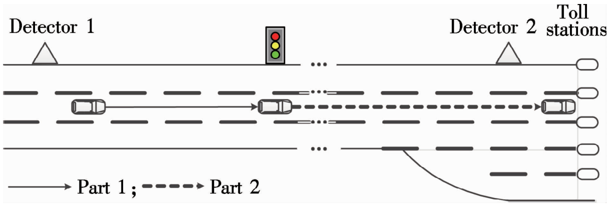

Fig. 2 Passing process of vehicles from queuing to passing through toll station

Part 1 is the process of vehicles from queuing to passing through traffic control lights, in which vehicles pass in batches, and then

$$Q = \frac{a(N-n)}{s} + \frac{n(L_1 + a)}{s} \tag{1}$$

$$T_1 = \frac{nx}{a(N-n) + n(L_1 + a)} \tag{2}$$

where Q is the traffic volume of each batch; T_1 is the stop times of vehicles from queuing to passing through traffic control lights; N is the number of channels of working entrances of a toll station; n is the number of mainlines; s is the average space headway.

Part 2 is the process of vehicles from passing through traffic control lights to passing through toll stations, in which vehicles are in a state of slowly moving traffic. Due to the short length of this section, the stop times of a vehicle in this section is approximately equal to the number of vehicles before it. The stop times of the vehicles of the same batch entering this section are different when they pass through a toll station due to their sequence passing through the toll station. Then

$$T_2 = \frac{(N-n)\sum_{i=1}^{a/s} i + n\sum_{i=1}^{(L_1+a)/s} i}{\frac{(N-n)a}{s} + \frac{n(L_1+a)}{s}} = \frac{a^2(N-n) + n(L_1+a)^2}{2as(N-n) + 2ns(L_1+a)} + \frac{1}{2} \tag{3}$$

where T_2 is the stop times of vehicles from traffic control lights to passing through toll stations, and T is the stop times of vehicles from queuing to passing through toll stations.

$$T = T_1 + T_2 = \frac{nx}{a(N-n) + n(L_1 + a)} + \frac{a^2(N-n) + n(L_1+a)^2}{2as(N-n) + 2ns(L_1+a)} + \frac{1}{2} \tag{4}$$

4.2 Stop times optimization method and solutions of control system parameters

The derivation of Eq. (4) with respect to L_1 can be expressed as

$$\frac{\partial T}{\partial L_1} = n(L_1 + a)^2 - 2a(L_1 + a)(N-n) - (N-n)a^2 - 2nsx \tag{5}$$

Let $\frac{\partial T}{\partial L_1}$ equal 0, and the critical value of L_1 can be calculated as

$$L_1 = \frac{(N-n)a \pm \sqrt{a^2(N-n)^2 + na^2(N-n) + 2n^2sx}}{n-a} \tag{6}$$

Substituting Eq. (6) to Eq. (4), the optimal solution of stop times T can be obtained.

In order to ensure that vehicles pass through toll stations without incremental time, the first vehicle of the follow-up batch must arrive at the toll station to receive charging service as soon as the final vehicle of the former batch has completed charging service, so

$$L_1 + a = \frac{L_2}{s} t\bar{v} \tag{7}$$

$$L_2 = \frac{s}{t\bar{v}}(L_1 + a) \tag{8}$$

where t is the average charging time of a toll station, including service time and departure time[15]; $\bar{v}$ is the average speed of the vehicles passing through L_2, and the speed of 20 km/h is selected for analysis.

An inspection of (6) and (8) reveals that, the vehicle queue x in the upper reach of traffic control lights leads to the optimal position of the traffic control light and Detector 2.

5 Case Study of Traffic Control System

5.1 Parameters of traffic congestion and area at toll stations

A field case study of the toll station (entrance to Tianjin) of Tianjin-Baoding Expressway on the slowly moving traffic caused by expressway closure was made. It includes the following parameters: space headway, vehicle composition, vehicle arrival rate, service time, number of channels and mainlines, speed limit and number of vehicles per hundred meters[16].

Taking the above parameters as the basic data for the Paramics simulation, the congested traffic flow at the initial stage of the release of the Tianjin-Baoding Expressway toll station was simulated. To find stop times of vehicles passing through the toll station, four cars in the model that began to queue were tracked and their stop times were averaged. The detailed values of traffic parameters are shown in Tabs. 2 to 4.

Tab. 2 Traffic volume parameters of Paramics simulation system

Vehicle type	Heavy truck	Medium truck	Small truck	Bus	Medium bus	Car
Traffic volume/ (veh · min^{-1})	3.51	1.2	2.85	0.21	0.18	10.89

Tab. 3 Traffic parameters of Jinbao Expressway (Tianjin Section)

Parameters	Survey value
Length of toll square a/m	79
Number of channels N	4
Delay time t_D/min	50
Average space headway s/m	11
Number of mainlines n	2
Average time t between adjacent startings/s	18

Tab. 4 Simulation results of Paramics

Parameters	Simulation value
Queue length L/m	2 000
Average number of stops	175.2

According to Eq. (6),

$$L_1 = 237.66 \text{ m} \tag{9}$$

The distance from the toll station to the location where the traffic light is set is defined as L', then

$$L' = L_1 + a = 316.66 \text{ m} \tag{10}$$

L_1 and other parameter values are substituted into Eq. (8),

$$L_2 = 34.8 \text{ m} \tag{11}$$

5.2 Analysis of traffic control system effects

To analyze the effects of the traffic control system, the fuel consumption of cars was investigated, and the results show that their start fuel consumption is 27.6 mL and idle fuel consumption is 0.23 mL/s.

5.2.1 Traffic status without traffic control system

The traffic status without the traffic control system is simulated in Paramics, as shown in Tab. 4, in which the stop times $T = 175.2$.

The delay time of vehicles passing through the toll station is 50 min, which can be approximately considered as the idle time D. Given the start and idle fuel consumption, the fuel consumption M of vehicles passing through the toll station can be calculated, namely

$$M = 27.6T + 0.23D = 5\ 525.7 \text{ mL} \tag{12}$$

5.2.2 Traffic status with traffic control system

The parameters, such as the number of mainlines and channels and square length, are substituted into Eq. (4) to calculate stop times $T = 17.07$.

With the traffic control system, the vehicles passing through the toll stations need to start 17.07 times, so the total idle time

$$D = tT = 307.26 \text{ s} \tag{13}$$

The parameter values $T = 17.07$ and $D = 307.26$ s are substituted into Eq. (12), and the fuel consumption of the vehicles passing through the toll station is calculated as

$$M = 541.8 \text{ mL} \tag{14}$$

The comparison of stop times and fuel consumption in these two statuses shows that: without the traffic control system, the vehicles passing through the toll station parked 175.2 times, and the fuel consumption per vehicle was about 5 525.7 mL; with the traffic control system, the vehicles passing through the toll station parked 17.07 times, and the fuel consumption per vehicle was about 541.8 mL. With the traffic control system, the stop times and fuel consumption of the vehicles passing through the toll station are 1/10 of the original values.

5.3 Optimal parameter selection for different queue lengths

Tab. 5 presents the optimal location selection of traffic control lights and Detector 2 for the queue of different lengths at toll stations. According to the most frequent queue length, the parameters of the system can be set, referring to Tab. 5.

Tab. 5 Traffic control system parameter selections m

L = 1 000 m			L = 1 500 m			L = 2 000 m		
L_1	L'	L_2	L_1	L'	L_2	L_1	L'	L_2
185.69	264.69	29.12	213.26	292.26	32.15	237.66	316.66	34.83
L = 2 500 m			L = 3 000 m			L = 3 500 m		
L_1	L'	L_2	L_1	L'	L_2	L_1	L'	L_2
259.77	338.77	37.26	280.14	359.14	39.56	299.14	378.14	41.59

6 Conclusions

1) This traffic control system is designed to significantly reduce start and idle fuel consumption without increasing passing time by reducing stop times and idle time. Based on the analysis of the relationship among the parameters of the traffic control system, this system aims to minimize fuel consumption and find optimal parameters through functions.

2) The comparison of the stop times and the fuel consumption with and without the traffic control system shows that, with the traffic control system, the stop times and the fuel consumption of the vehicles passing through the toll station are 10% of the original values. Finally, the optimal parameter selection programs of the traffic control system for different queue lengths are given using the optimal parameter calculation model.

3) The proposed traffic control system can significantly reduce fuel consumption in traffic congestion at toll stations, which is in accordance with the national policies on energy conservation and emission reduction.

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基于环境友好理念的高速公路收费站前路段拥挤车流控制办法

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摘要:以缓解因高速公路收费站站前路段拥挤车流并由此带来的能源消耗加剧与排放物激增等问题,基于环境友好理念,提出了一种新型控制办法. 首先,基于调查结论、交通流理论和车辆感应技术,确定了将缓慢行进车流向分段放行车流引导的技术路线. 建立了停车次数模型,以燃料消耗最小化为目标,对模型中的参数进行了优化,并对收费站前车辆不同排队长度情境下的交通控制信号灯、检测器 2 的最佳布局位置进行了计算. 最终,通过 Paramics 仿真软件对此拥挤车流控制技术的效果进行了验证. 结果显示,此控制系统可以有效减少收费站通行车辆 90% 的燃料消耗.

关键词:交通工程;交通拥堵;交通流理论;收费站;燃料消耗

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