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Study on Compound Toll Station of Expressway

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Abstract
At present, the expressway toll station is designed as a single-storey structure. Due to the limitation of land area, the number of toll lanes can not be expanded on the existing area.Therefore, in order to make full use of the three-dimensional space of highway toll station as the starting point, this paper puts forward the assumption of double three-dimensional toll station.The structure of double - layer toll station is designed through reasonable space layout.Each floor of the toll station corresponds to a one-way traffic flow in one direction and is connected to the main road via a ramp.By assuming the traffic flow, the paper compares the service level of the single-layer toll station with that of the double-layer stereo toll station.The layout of the double-layer stereo toll station can improve the service level under the same conditions,and also considers the traffic safety and environmental friendliness.Compound three-dimensional toll station ensures the rapid passage of vehicles, reduces congestion, reduces idle running time of vehicles, reduces vehicle exhaust emissions, and at the same time reduces the area of toll station, providing a green energy saving option for the sustainable development of the environment.

Keywords:*expressway,double toll station,service level,green energy saving*

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I. INTRODUCTION

With the improvement of people's living standards, the number of private cars has increased rapidly, and at the same time, the state has implemented a free policy for highway passenger cars on holidays, and reports of congestion on some highways during holidays have become common. Especially in tourist cities, congestion at expressway toll booths during peak holiday periods is an urgent problem to be solved (Figure 1). In recent years, the congestion and queuing phenomenon at the entrances and exits of expressway toll stations have received widespread attention, which not only prolongs the travel time of expressways, affects the psychology of drivers, but also brings hidden dangers to driving safety. In addition, the car idles in congested conditions, and the fuel cannot be fully burned, which increases air pollution.

Figure 1 Expressway toll booth exit on holidays

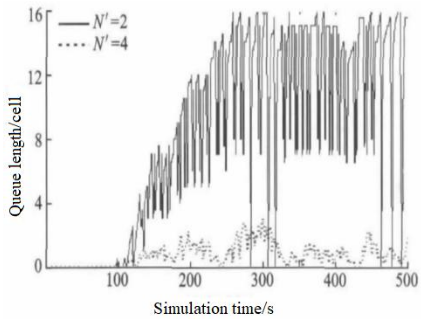

Figure 2 Comparison of queue lengths for different toll channels

Most of the research on congestion starts from the aspect of highway control strategy [1], and relatively little attention is paid to the hardware of expressway toll entrances and exits. Zhang Chenchen et al. [2] studied the different influencing factors of congestion at the main line toll booth through model simulation, and found that when the number of expressway toll lanes opened increased from 2 to 4, the queue length decreased significantly (Figure 2). It can be seen that the expressway toll channel accounts for a significant proportion of whether the road is congested.

At present, the domestic highway toll station is mainly a single-layer toll station, if the toll station is reasonably spaced, the single-layer toll station is transformed, the upper space is effectively used, and the double-dimensional toll station is changed, the congestion status of the entrance and exit of the expressway toll station will be greatly alleviated, which is the starting point of this study.

II. DESIGN IDEAS AND PRINCIPLES

With the rapid increase of vehicles, the traffic volume of many expressway toll stations significantly exceeds their design capacity, resulting in increasingly prominent congestion problems at toll booths, which seriously affects the traffic rate of high-speed traffic trunk roads. Especially for some large cities, land resources are limited, and the rational use of toll station design space is particularly important. In order to solve the congestion of the expressway and ensure its traffic efficiency, after analyzing the factors of traffic performance, structural rationality and driving safety, the M/G/K model and mathematical analysis method are used to test the service capability of the toll station [3], the double-dimensional toll station model is designed and constructed, the design parameters are verified, and the project is proposed for transformation according to the research conclusion.

Make full use of the upper space of the toll station, build a double-type three-dimensional toll station, increase the number of toll lanes, expand the toll capacity of the toll station, and fundamentally solve the problem of traffic congestion at the entrance and exit of the toll station.

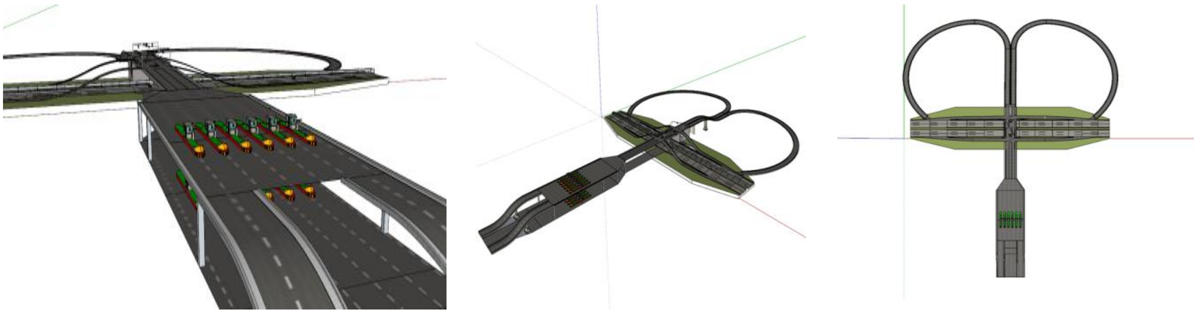

Figure 3 Model of duplex three-dimensional toll station

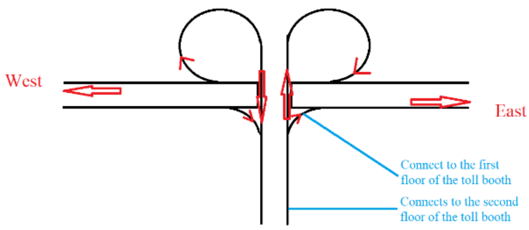

Figure 4 Traffic flow diagram

The model of the toll station is shown in Figure 3, the first and second floors lead to different directions of the expressway, and there are corresponding signs before entering the toll booth, indicating the direction of the lane, guiding the driver to choose the toll gate of the destination by himself, separating the traffic flow, and alleviating the traffic pressure of the toll booth. In order to avoid emergencies, the model also has emergency passages and traffic signs to minimize the occurrence of congestion, as shown in Figure 4.

III. RESULT AND DISCUSSION

3.1 Passage efficiency analysis

The research of duplex three-dimensional toll stations is mainly to improve the traffic capacity and service level of expressway toll stations, so as to improve the traffic capacity of the entire expressway section. In order to intuitively compare and analyze the traffic capacity of two different forms of toll stations, single-storey and double-dimensional toll stations, we need to study the traffic characteristics and traffic characteristics of double-level three-dimensional toll stations, and then compare the service level of the two types of toll stations through M/G/K models and mathematical analysis methods [4].

3.1.1 Traffic characteristics of duplex three-dimensional toll stations

The duplex three-dimensional toll station will transform the traditional single-level toll gate. While increasing the toll lane, the traffic form of vehicles is also changed, and the toll gate is divided into two levels according to the direction of traffic flow on the highway. The lower toll station is mainly used for toll services for vehicles entering and exiting in the A→B direction on the highway, and the upper toll station is used for the toll service for vehicles entering and exiting in the B→A direction on the highway. The traffic flow characteristics of vehicles entering and exiting the expressway are introduced.

(1) The traffic characteristics of vehicles entering the expressway

Main road vehicles will receive signs in advance when approaching the toll booth, and can freely choose according to the different vehicles arriving at the destination. After that, the vehicle gradually slows down into the upper or lower toll booth, paying attention not to overtaking or cutting the queue. After the layering is completed, vehicles enter the toll plaza along the widened lane, and choose the toll lane with high traffic efficiency to avoid traffic congestion caused by stranded vehicles. After the toll is completed, the vehicle drives directly into the ramp to the highway.

(2) Traffic characteristics of vehicles exiting the highway

Vehicles will receive signs when approaching highway exits, after exiting the highway and following the ramp into the toll booth. The A→B ramp leads to the first floor toll booth, and vehicles in the direction of B →A can directly follow the ramp to the second level toll booth. When entering the toll plaza, vehicles choose the toll lane with higher traffic efficiency. After the service is completed, the lower vehicle enters the main road directly, the upper vehicle enters the downhill along the narrowed lane on the right, and accelerates into the main road after the downhill is completed.

3.1.2 Comparison of traffic capacity at the same design volume

By using the M/G/K vehicle queuing theory based on the mathematical characteristics of traffic flow, the delay time of the two types of toll booths under the proposed annual average daily traffic volume is calculated. Compare the service levels of the two to determine the efficiency improvement effect of the double-entry toll booth.

(1) Proposed highway toll booths, with a service level of three [5, 6]. The main form of charge is manual fee change. The average daily traffic volume is 20,000 vehicles/d. The traffic is 75% for small cars, 15% for medium-sized cars, 3% for large cars, and 2% for oversized cars.

(2) Propose the number of toll lanes for traditional toll booths

1) Traffic volume

The actual toll lane should be drawn up using the design hourly traffic volume at the time of the main line design, and the hourly traffic volume is the number of vehicles passing through the road section during the calculation period in hours.

DDHV=AADT×K×D=20000×0.09×0.5=900 units/h

DDHV: Design hourly traffic; AADT: Average Annual Daily Traffic; K: Design hourly traffic coefficient, take K=9%; D: Directional unevenness coefficient, take D=0.5.

2) One-way equivalent incoming intensity

Minibus: A1 = 75%, E1 = 1.0

Midsize cars: A2 = 20%, E2 = 1.05

Large cars: A3 = 3%, E3 = 2.0

Trailer: A4 = 2%, E4 = 2.5

M=∑(Ei-1)Ai= 0.07

SFe = DDHV(1+M) = 225× (1+0.07)=963 units/h

Ai: proportion of traffic composition; Ei: Toll station vehicle conversion factor (Table 1); SFe: Equivalent oncoming strength in one direction.

Table 1 Conversion factors for toll booth vehicles

Models	Vehicle conversion factor								
	Pay thechange			Card collection/ticket verification			One-size-fits-all		
	≤70	≤140	≤220	≤250	≤400	≤480	≤100	≤300	≤380
Minibus	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Mid-size car	1.15	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Large car	2.5	2.5	2.0	2.5	2.5	2.0	2.5	2.5	2.0
Trailer	3.0	3.0	2.5	3.5	3.5	3.0	3.5	3.5	3.0

3) Service traffic

Check Table 2 to know:

MSF=220pcu/h/lane

MSF: Maximum service traffic at the Level III service level.

Table 2 Toll booth service level classification table (payment change)

Service levels	Average delay(s), d	Maximum service traffic (passenger car h), MSF
Ⅰ	*d*<35	70
Ⅱ	35≤*d* <70	150
Ⅲ	70≤*d* <150	220
Ⅳ	150≤*d*	220

4) Determine the number of toll lanes

$$N=Int\left(\frac{SFe}{MSF}\right)+1=5$$

N: The number of lanes at the toll booth.

(3) Calculate the service level of the duplex highway toll booth

The above-mentioned proposed traditional form toll booth is now replaced by a duplex toll booth. Due to the spatial expansion of the toll station, the number of one-way lanes N=10 calculates the delay time and service level of the double-entry toll station. Due to the uncertainty of the vehicle's destination, the traffic flow of the proposed vehicle in both directions of the highway is evenly distributed, and it should be reduced in actual calculation.

1) Rush hour traffic

The above calculated hourly traffic is off-peak traffic, so you need to convert it to peak hour traffic:

SF = Q/PHF15 = 971 units/h

SF: actual peak hour traffic; Q: Observe hourly traffic, take the above design hourly traffic; PHF15: 15-minute peak-hour coefficient, the value is shown in Table 3, and it is proposed to be the average value of plain microhills.

Table 3 15-minute peak hour coefficients

Terrain conditions	Eastern region	Central region	Western region	National average
Plain micro-mounds	0.935	0.926	0.928	0.927
Mountains and hills	0.901	0.875	0.846	0.874

2) Average intensity of incoming vehicles

Number of lanes N=10,

Minibus: A1 = 75%, E1 = 1.0

Midsize cars: A2 = 20%, E2 = 1.05

Large cars: A3 = 3%, E3 = 2.0

Trailer: A4 = 2%, E4 = 2.5M = Σ (Ei−1)Ai = 0.07

$$SFe=\frac{SF}{N}(1+M)=104\text{units/h}$$

$$\lambda=\frac{SFe}{3600}=0.0289$$

3) Calculate the average delay

$$d=\frac{D[T]+E[T]^2}{2E[T](N-\lambda E[T])}\left[1+\sum_{i=0}^{N-1}\frac{(N-1)!(N-\lambda E[T])}{i!(\lambda E[T])^{N-i}}\right]^{-1}=41$$

λ : average oncoming intensity;

E[T] – the expectation of service hours;

D[T] - variance of service hours, see Table 4

Table 4 Characteristic parameters of service time distribution of various toll lanes

Service Time Characteristic Parameter Toll Station Type	Minibus		Mid-size car		Large car	
	$E[T]$, s	$D[T]$, s^2	$E[T]$, s	$D[T]$, s^2	$E[T]$, s	$D[T]$, s^2
Closed fee change	16.3	7.47	20.0	10.56	26.3	17.36

Closed card collection/ticket verification	7.6	0.71	9.7	0.99	14.0	1.87
One-size-fits-all toll stations	9.4	2.10	13.9	5.44	19.2	8.08

4) Determine service levels

Taking into account the widening of the lanes for vehicles entering the toll booth and the downhill slowdown of driving away from the toll booth. Here, the calculated average delay is increased, and the proposed increase value is α=5s.

$D=d+\alpha=46s$

d: Calculate the average delay; α: Consider the delay caused by the structural form of the duplex toll station.Looking at Table 5, it can be seen that 35⩽D<70, so the service level is level 2.

Table 5 Service level classification table of toll booths (change payment)

Service levels	Average delay(s), d	Maximum service traffic (passenger car h), MSF
Ⅰ	d<35	70
Ⅱ	35⩽ d <70	150
Ⅲ	70⩽ d <150	220
Ⅳ	150⩽ d	220

From the above analysis, it can be seen that under the condition of occupying the same area, the double-level three-dimensional toll station increases the number of toll channels through the upper layer, which plays the role of expansion and diversion, which can effectively reduce the delay caused by toll collection, improve the service efficiency of toll stations, improve the traffic capacity of expressways, and effectively improve the service level of expressway toll stations.

3.2 Driving safety aspects

The model has no collision and interweaving of traffic flow, strong traffic ability and driving safety; For drivers, the driving direction is easy to identify and not easy to get lost, which can reduce traffic accidents caused by driving direction errors, and also effectively save driving time.

3.3 Energy conservation and emission reduction

Under the influence of road construction, traffic accidents, traffic demand fluctuations and other factors, traffic congestion and slowing down often occur, especially near toll stations with large traffic flow, and the main line vehicles of the expressway are disturbed by queuing service vehicles, often forming large-scale congestion, frequent stoppages, and long-term idling. According to statistics, the starting fuel consumption of the vehicle is 3 ~ 6 times of the normal fuel consumption, and the fuel consumption of idling and slowing through the congested road section is 16 ~ 20 times that of the normal pass, so traffic congestion and slow driving will cause serious fuel waste, and the fuel can not be completely burned in the low-speed driving of the vehicle, and the exhaust emissions will increase, causing environmental pollution. The duplex three-dimensional toll station makes reasonable use of the upper space of the expressway toll station, expands the capacity of the toll station, and adopts the method of driving to the direction of the circulation to greatly reduce the number of starting brakes and idle time of the vehicle, so as to achieve the purpose of saving energy and reducing exhaust emissions.

3.4 Land-saving aspects

In the case of increasingly tight land resources, the scale of highway toll station land has been basically determined in the course planning, and it is impossible to expand the number of toll booth channels in the plane within the given area, and add a layer of toll channels in the three-dimensional direction, saving valuable land resources, especially for first-tier cities with a lot of land, the double-dimensional toll station has more promotion value.

IV. CONCLUSION

Nowadays, the load of the transportation system is increasing, the problem of highway traffic congestion is becoming more and more serious, and the double-dimensional toll station can alleviate the traffic pressure by maximizing the use of the construction space. Especially for areas with limited land resources and large traffic flow, making full use of the upper space is an effective measure to improve the service level of expressway toll stations. The double-level three-dimensional toll station can be used for the renovation of the old toll station or the new construction of toll station in areas with lack of land resources, which is forward-looking, meets the requirements of safer and more efficient operation of the transportation system, conforms to the new era concept of energy conservation and emission reduction, and has application and promotion value.

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