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Research Article

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Analysis of Road Capacity Modeling and the Impacts of Vehicle Performance

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ABSTRACT

This paper deduced the mathematical model for road capacity under the conservative and moderate behavior patterns, analyzed the relationship between the vehicular gap and the dynamic performance of the vehicle as well as the impacts of the improvement of vehicle performance on the vehicular gap. Meanwhile, based on the mathematical model established, it analyzed the impacts of the dynamic performance and the operation stability of the vehicles on the traffic capacity: the widespread application of advanced technology such as reliable mechanism design, ABS and automatic gear shifting, is advantageous to reduce the vehicular gap and improve the traffic capacity; the departure flow rate at the intersection will increase with the improvement of the accelerating ability of the vehicles; the realization of formation driving technology in the coming future will further upgrade the traffic capacity by leaps and bounds.

Keywords: mathematical model, road capacity, vehicle performance, automobile dynamics .

INTRODUCTION

China started to investigate and analyze the traffic capacity of the basic expressway section around 2000, which was closest to the traffic condition; meanwhile, the relatively systematic study on the design capacity of the mixed traffic double lane highway was launched in 1984 of the last century[1]. Almost all studies separate the highway from the urban road to reflect the differences between the continuous flow and the intermittent flow. The basic highway section is selected as the representative section and the grade crossing as the "bottleneck" of the traffic capacity is the study subject of the traffic capacity of urban road. It is indicated by the existing findings that the research thoughts adopted by both of them are identical[2][3], and it is an indispensable even exclusive approach to observe the continuous traffic volume at the crowded section in busy hour. The curve fitting is carried out for the continuously observed flow data and the peak value of the curve is just the traffic capacity of the section. The expressway net has not reached the saturated state up to now. Different from the sparse flow on the expressway, the urban road users increase rapidly, especially, the traffic congestion in big cities is becoming more and more serious, as a result, the traffic capacity of the urban road crossing and the section can be easily determined[4]. It is indicated by the related data from USA that the basic traffic capacity had risen from 1400pcu/h/ln in 1960s to 2200pcu/h/ln[5] in 2002 in nearly 40 years, however, the road net had been basically built up in 1960s-1970s, so the most possible reason for the rise in traffic capacity by 60% is the vehicle performance factors, namely the improvement of dynamic performance and operability of the vehicle.

EXPERIMENTAL SECTION

1. Analysis of Traffic Capacity Based on Dynamic Performance of Vehicle

Viewed from the C microscopic angle, space headway S and vehicle speed V jointly determine the traffic capacity, denoted by $C=3600/(S/V)_{min}$. Although the vehicle speed V and the space headway are the results of the subjective choices of the drivers, the one dominating the decision-making process is his/her understanding of the vehicle performance and the capability and confidence in controlling the vehicle.

1.1 Analysis of traffic capacity at the highway section with conservative driving behavior

The observed results on the highway section and the questionnaires for the drivers verify that quite a number of drivers are apt to determine the space headway "S"with the "most unfavorable principle", that is to say, it is held by them that the leading vehicle may come to full stop suddenly, in this way, the braking deceleration of the leading vehicle is infinitely great. The traffic capacity of the highway section based on this kind of driving behavior is analyzed as follows, where the space between the current vehicle and the leading vehicle at time "t" is [6][7]:

$$S(t)=V^2(t)/(2a)+L+T_0\times V(t) \quad (1)$$

The time headway can be derived from Formula (1):

$$h(t)=V(t)/(2a)+L/V(t)+T_0 \quad (2)$$

Then: $dh(t)/dV(t)=1/(2a)-L/V^2(t)$

When $dh(t)/dV(t)=0$, $V(t)_m=\sqrt{2aL}$ (3)

Obviously, when $V(t)=V(t)_m$, h(t) is minimum. Substitute $V(t)_m$ into Formula (2) and then:

$$h(t)_{min}=\sqrt{2L/a}+T_0 \quad (4)$$

Thus: $C_{con}=3600/(\sqrt{2L/a}+T_0)$ (5)

Where: S(t)—space headway; V(t)—vehicle speed; a—braking deceleration; h(t)—time headway; C_{con}—traffic capacity in conservative driving; L—stopping headway; $L=L_V+d, d\in(1,5)$; L_v—Overall length of vehicle; T_0—lag time, $T_0=T_{cle}+T_{lep}+T_{mov}$; T_{cle}—clearance elimination time; T_{lep}—response and judgment time; T_{mov}—footstep movement time. Generally, the braking deceleration of the modern vehicle can reach 5.8-6.5m/s2, which is much higher than the one in 1960s [8]-[10]. Given $a=6m/s^2$, L=8m, and then substitute them into Formula (3), then $V(t)_m$=10.2m/s=37km/h . In case of car-following driving, the driver's response is relatively prompt. Given T_0=0.6s, substitute it into Formula (4) and then $h(t)_{min}$=2.16s. Finally, C_{con}=1660pcu/h/ln can be derived from Formula (5).

1.2 Analysis of traffic capacity at the highway section with moderate driving behavior

Different from the conservative drivers, the moderate drivers are more willing to select the car-following driving to keep a proper space, who account for a largest proportion. It has been held by the moderate drivers that the brake distance of the leading vehicle may be a little shorter[11][12]. In order to reflect this fact in the model, given $a_2>a_1$ and the stopping headway is not changeless and is related to the current traffic environment and the vehicle speed, then the space headway model in a common sense can be obtained:

$$S(t)=\frac{V^2(t)}{2}\times\frac{(a_2-a_1)}{a_1a_2}+(L_0+\beta\times V^k(t))+T_0\times V(t) \quad (6)$$

In the formula:β,k—regression parameter; a_1—braking deceleration of the vehicle; a_2—braking deceleration of the leading vehicle; $L_0=L_v+0.5$, and the meanings of other symbols are same as the ones foregoing.

When $a_2\to+\infty, k=0$ in Formula (6), Formula (6) becomes Formula (1) in form, in other words, Formula (1) is a special case of Formula (6). Actually, the model for the risky drivers selecting the space can be derived from Formula (6), at this point, $a_1\approx a_2$ even $a_1>a_2$. The first item in Formula (6) is 0 or negative.

The time headway can be derived from Formula (6):

$$h(t)=\frac{V(t)}{2}\times\frac{(a_2-a_1)}{a_1a_2}+(L_0/V(t)+\beta\times V^{k-1}(t))+T_0 \quad (7)$$

And then, $$dh(t)/dV(t)=\frac{(a_2-a_1)}{2a_1a_2}-L_0/V^2(t)+(k-1)\beta\times V^{k-2}(t) \quad (8)$$

When $dh(t)/dV(t)=0$, the expression of $V(t)_m$ cannot be deduced from Formula (8) at present. However, it is not difficult to derive $V(t)_m$, then $h(t)_{min}$ and C_{mod} through computer programming(C_{mod}, the traffic capacity in moderate driving). Note that $a_1$and a_2 in the numerator and denominator of the first item in the formula shall be distinguished in solving a_1,a_2 Formula (8), in the numerator, $a_2>a_1,a_2-a_1$ is related to the moderation degree of the driver and in the denominator is just related to the vehicle performance; it is of the same model of car, it can be processed into $a_1=a_2$, thus Formula (6) can be expressed as:

$$S(t) = \frac{V^2(t)}{2} \times \frac{\Delta a}{a^2} + (L_0 + \beta \times V^k(t)) + T_0 \times V(t) \quad (9)$$

With the basic expressway section as a case study,given $\beta=0.9$,$k=0.5$,$T_0=0.6s$,$a=6.5m/s^2$,$\Delta a=3m/s^2$, through iterative computations with computer, V(t)m=49km/h, h(t)min=1.457s, C_{mod}=2400pcu/h/ln can be derived.

1.3 Analysis of traffic capacity based on the integrated consideration of two kinds of driving behaviors
Since the risky drivers account for a very small proportion in the totality, based on the previous study, it is defined that the conservative drivers account for 25% and the moderate drivers account for 75%, without any consideration of the effects of the risky drivers, the following formula can be derived:

$$C=C_{con}\times 25\%+C_{mod}\times 75\%=1660\times 25\%+2400\times 75\%=2215pcu/h/ln \quad (10)$$

It is very approximate to 2200pcu/h/ln provided by Literature [5], proofing the validity of Formula (9) and (10), which can be used as the basis of theoretical analysis and engineering design. It is necessary to pay attention to the difference in the driving sight distance between Formula (1) and (9) and the engineering design, among which Formula (1) and (9) reflects the characteristics of subject behaviors of the drivers and are the results of the subjective choices of the drivers, essentially differing from the driving sight distance.

2. Analysis of Traffic Capacity of Urban Road (intersection)
In case of random arrival or uniform arrival, the traffic capacity C_{ins} at the intersection is the product of the departure flow rate q_g and the green ratio λ when the green light is on. At the beginning when the green light is on, the time headway includes the starting loss time T_s and the impacts of the starting loss time T_s will decrease gradually with the continuous green time because the vehicle at relatively far position may be accelerated relatively adequately when arriving at the stop line. The study regarding the planning and control of the intersection has been relatively matured, so the theoretical formulas are not deduced in details here.

The essential difference between departure from the intersection and the driving on the section is that there may be sufficient space on the section for the drivers and the free (or relatively free) driving opportunity, so the characteristics of the subject behaviors of the drivers have the space for performance, meanwhile, it can be deemed that the behavior characteristics of the drivers are basically identical in departure from the intersection and the individual differences can be ignored because the narrow space in starting forces the driver to follow the leading vehicle. Therefore, the traffic capacity at the intersection is directly correlated to the starting loss time and accelerating ability of the vehicle, but seems a little correlated to the braking performance. However, when the left turn phase of the vehicle is shared with the pedestrian crossing, considering the avoidance for the pedestrians, the braking performance has a certain effect on the traffic capacity of the left turn phase.

3. Impacts of Dynamic Performance and Operation Stability of Vehicle on Traffic Capacity
3.1 Analysis of traffic capacity at intersection
100km accelerating time T_a of the vehicle is a parameter that the vehicle users concern. In the opinions of the experts and the auto-fans, T_a has been accurate to 1/100s, the upgrading of the traffic capacity at the intersection in the past decades of years has been mostly attributed to accelerating time T_a and the reduction of starting loss time T_s besides the signal timing optimization. With the further improvement of the vehicle performance, T_a and T_s will fall down still, resulting in the increase in departure flow rate q_g[13].

3.2 Impact of improvement of vehicle performance on traffic capacity of the basic section
a,L,β,K,T_0 in Formula (1) and (9) are closely correlated to the vehicle performance, among which a is the measurement of the braking performance, the stopping headway is also affected by the braking performance and transmission clearance overcome time T_{cle} contained in T_0 depends on the model of mechanism.

3.2.1 Impact of changing T0 on traffic capacity
Transmission clearance overcome time T_{cle} accounts for a relatively large scale in T_0, however, advanced mechanical design theory and manufacturing process make the cooperation among the mechanism more stable and excellent, the related study on the transmission mechanism with the automatic clearance compensation function has been made and T_{cle} will reduce continuously in the coming future. Electronic control units can substitute for some or all functions of the transmission mechanism, as a result, the complicated transmission mechanism is not required any more. So, the electronic control technology of the vehicle may reduce T_{cle} to approximately 0. It can be seen from Formula (1) and (9) that $T_{cle}\times V(t)$makes great contributions to the vehicular gap.

Due to the mature of the constant variable transmission technology and automatic transmission technology, the clutch will be cancelled step by step, as a result, the footstep movement time T_{mov} required for movement from the throttle to the brake paddle is naturally removed from T_0, then, at last, T_0 only contains the response and judgment time T_{rep} of the driver. In case that T_0 falls down from 0.6s at present to 0.2s, the traffic capacity in conservative driving calculated through Formula (1) will increase from 1660pcu/h/ln to 2040pcu/h/ln and the one in moderate driving calculated through Formula (9) will increase from 2040pcu/h/ln to 3380pcu/h/ln, and the weighed traffic capacity C=2040×25%+3380×75%=3045pcu/h/ln.

3.2.2 Impact of a and L on traffic capacity

The reliable design of the braking mechanism and the widespread application of ABS upgrade the braking performance and directional stability of the vehicle and endow the drivers with more trust in the brake system. As to the traffic capacity, the rise in braking strength a will directly cause the conservative drivers to select the relatively small vehicular gap, which is reflected in the reduction of the first item in Formula (1); the same to the moderate drivers, in case that Δa in Formula (9) remains unchanged, a little rise in a will lead to the reduction of the first item in Formula (9) to a large extent. However, it can be seem at the same time that the space for further upgrading the modern vehicle a is very small just because a cannot exceed the static top adhesive capacity between the tyre and the road surface, namely $a \le f_s \times g$, so the control over the directional stability in the braking process may be an important study direction in the coming future. All of these things will increase the confidence of the driver, which is reflected in the reduction of the safe stopping distance regarding the traffic capacity, such as the reduction of L in Formula (1) and the change in the fitting parameter β,k in Formula (9). Relative to the braking strength a, the safe stopping distance can be reduced to a certain extent, thus the traffic capacity may greatly rise.

3.3 Impact of automatic driving technology on traffic capacity[14][15]

Formula (1) and (9) are based on the subjective thinking and response of the driver. When the driving speed V(t) rises ($V(t)>V(t)_m$), in order to avoid the serious collision, it is necessary for the driver to select larger vehicular gap, thus the road capacity tends to fall down, in case that the relatively small gap at low speed is still remained even at relatively high speed, the road capacity is of positively linear correlation to the vehicle speed; or in case that rise in vehicle speed V(t) exceeds the one in vehicular gap, the counteraction of S(t) upon the road capacity will be restricted, the road capacity will increase with the rise in V(t), which is obvious according to the formula C=3600/(S/V).

The automatic driving technology (formation driving) makes it possible to change the design, namely the substitution of Electronic Control Unit for the driver to operate the vehicle, including the adjustment of driving route and speed. The program will calculate the minimum safe vehicular gap $S(t)_{Que}$ at formation running speed V_{Que}, then keep the gap at $S(t)_{Que}$ through adjusting the current speed V(t) and finally run the vehicle at V_{Que}. $S(t)_{Que}$ calculated through the computer program is significantly smaller than S(t) obtained through the subjective judgment of the driver, resulting in the high speed running with high density. At present, the study on the technology has entered the stage of road experiment and it has been proven in the basic expressway section controlling entrance and exit, however, it shall be further perfected before it is applied to the urban road with complicated traffic environment. When this technology is popularized, the road capacity will be certainly raised to the max. capacity on record and it is hopeful that the traffic capacity of the basic expressway section exceeds 4000pcu/h/ln.

RESULTS AND DISCUSSION

The traffic volume accommodated by the existing road net is nearly 60% more than that of 40 years ago. The upgrading of the dynamic performance and the operational stability of the vehicle may be the uppermost factors and every item in the mathematical model for the vehicular gap will be reduced correspondingly with the further improvement of the automotive technology, resulting in the increase in traffic capacity. In the coming future, due to the sustainable development and advance of the automotive technology, the dynamic performance and operational stability of the vehicle will be more excellent, the vehicle will win more trust from the driver and the operation will be safer and more reliable, all of which will be advantageous for the driver to select smaller vehicular gap. Therefore, the road capacity will consequentially increase in a sustainable manner in the coming future.

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