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RESEARCH PAPER

Modeling On-ramp Capacity with Driver Behavior Variation

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Abstract: Considering the variation of drivers' merging behaviors on the on-ramp of urban expressway, a gap acceptance theory model with variable critical gaps is proposed to measure the on-ramp capacity. When drivers travel along the acceleration lane of an on-ramp, the closer the driver is to the end of the acceleration lane, the stronger the driver's intention of merging into the main road would be, and a smaller critical gap will be selected. Consequently, the drivers' critical gap of merging decreases along with the acceleration lane of an on-ramp, which leads to the theoretical capacity of on-ramp at different position in the acceleration lane changed as well. Finally, a numerical example is given to illustrate the difference in capacity between the variable and fixed critical gap condition. The results indicate that the on-ramp capacity of the proposed model is always larger than those of the conventional model with fixed critical gap. Moreover, the above-mentioned difference is more obvious under oversaturation conditions.

Key Words: urban traffic; on-ramp; capacity; critical gap; driver behavior; urban expressway

1 Introduction

With the rapid growth of urban traffic demands, traffic jams appear in many cities of China to varying degrees, especially for Beijing, Shanghai, and other super-size cities. Some of these cities build large scale of urban expressways to improve the capacity of urban road network and to mitigate the traffic congestion. Ramp is a very important part of roadway, which was used to connect the expressway road network and common road network. Vehicles travel into the main road through on-ramp and interweave with the through-lane traffic. This usually leads to the traffic disturbance when flow rate in the main road is at a high level, and decreases the capacity of ramp segment with a road bottleneck formed. Therefore, exploring the capacity model of on-ramp will contribute to modeling the capacity of merging areas, and also benefit the evaluation of the capacity of ramp bottleneck sections.

Gap acceptance model is one of the primary methods in research of on-ramp capacity and has been widely used to estimate on-ramp capacity, un-signalized intersection capacity and traffic delay[1–4]. It assumes that the major road has priority, and the vehicle on the minor road can pass through or merge into the major road only when there is headway bigger than a threshold value (the critical gap); otherwise, drivers should stop to wait for a feasible one. The drivers' critical gap and following-up time are two important parameters which have significant effects on the on-ramp capacity in the gap acceptance model. There exist subjective and objective influence factors to the drivers' merge critical gap. In previous studies, researchers usually assumed that the parameter of critical gap obey some probability distribution to consider the difference between drivers' choice, and get a result that the capacity will decrease in this situation[5]. For the objective influence factors, researchers mainly consider the effect of waiting time on the drivers' patience and risk awareness[6,7]. The researches mentioned above are usually for considering the variable critical gap at un-signalized intersection. But for the drivers traveling through an acceleration lane, the choice of the critical gap is influenced not only by the waiting time before merging into the on-ramp, but also the length of the acceleration lane and the traffic status of the main road. Kita's investigation[8] presented that the drivers' critical gap changed when traveling along the acceleration lane for merge opportunity and pointed out the effect of the acceleration lane length on the critical gap value. In addition, the changes of main road headway distribution which caused by merging vehicles will also impact the drivers' merging behavior in the acceleration lane[9,10].

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In this paper, the gap acceptance model used in the earlier studies was also used here, and the effect of the length of the acceleration lane on driver's critical gap is well considered when investigating the on-ramp capacity model. Finally, a numerical study is given to analyze the impacts of different parameters on the capacity.

2 Gap acceptance model

Gap acceptance theory was first applied to study the capacity of minor road at un-signalized intersection, and later used to investigate the problem of capacity and traffic delay at on-ramp road sections. It assumed that the major road has priority, and the vehicle on the minor road can pass through or merge into the major road only when there is headway bigger than a threshold value (the critical gap); otherwise, drivers have to stop to wait for a feasible one. The classical minor road capacity model which is based on the gap acceptance theory is as follows:

$$C = q\int_0^{\infty} f(t)g(t)\mathrm{d}t \tag{1}$$

where C is the capacity of minor road, q is traffic intensity per unit of time in major road (pcu/s), $f(t)$ is the probability density function of headways t in the major road, and $g(t)$ is the function for the number of vehicles which can depart from the minor road during a gap of length t.

Let t_c be the critical gap of merging vehicles and t_f be the following-up time when minor vehicles sequentially merge into the major road. Therefore, within the major road gap t with the length $t_c \le t < t_f$ enables the merging of one vehicle from the minor road, and gap t with the length $t_c+(n-1)t_f \le t < t_c+nt_f$ enables n vehicle to merge. The merging probability expression is as follows:

$$P_n(t) = \begin{cases} 1, & t_c + (n-1)t_f \le t_c \le t_c + nt_f \\ 0, & \text{Otherwise} \end{cases} \tag{2}$$

Hence, the function for the number of vehicles which can leave the minor road during a gap of length t can be shown as:

$$g(t) = \sum_{n=0}^{\infty} n \cdot P_n(t) \tag{3}$$

3 Traffic characteristic of the on-ramp section

Combining with the field observation, traffic demand of urban expressways at on-ramps are very large, and causes serious traffic conflicts between merging vehicles from the acceleration lane and main road. Furthermore, there is a positive relation between the main road traffic flow rate and the on-ramp traffic flow. The characteristics of traffic flow here can be described as following:

(i) With a low flow rate of main road, on-ramp vehicles accelerate to merge into the main road, and the merging behavior has little impact on the traffic of main road.

(ii) With a large flow rate of main road, the car driver drives into the on-ramp at low speed and travel through the acceleration lane slowly to wait for an acceptable gap. Most of the vehicles can merge into the main road successfully before arriving at the end of an acceleration lane, and only a few of them arrive at the end and stop to wait.

(iii) When the main road has a heavy traffic jam, the traffic in the main road is in go-and-stop status and vehicles at the end of acceleration lanes will stop together with vehicles on the main road. Otherwise, even though the headway in the main road is closer to its minimum value, the on-ramp vehicles would still make a forced merge after a long queue is formed.

From the descriptions above, it can be found that the model with the assumption of priority in the main road and fixed critical gap did not consider the forced merge behavior at the end of acceleration lanes, and did not reflect the decreasing critical gap with increasing driving distance[8]. The changes of drivers' behavior could be regarded as the changes in the critical gap. As the drive distance increase, drivers' worry about stopping at the end of acceleration lanes will be strengthened. Hence, a smaller critical gap will be chosen.

4 On-ramp capacity model with consideration of drivers' behavior changed

4.1 Basic assumption

(i) There is an adequate traffic demand arriving at on-ramp without regarding to the traffic delay of vehicles out of on-ramp. It means that the distribution of vehicles' arrival has no impact on the merging opportunity, and vehicles can merge into main road once there is an acceptable gap appearing.

(ii) It is also assumed that the merging cars from acceleration lanes have no impact on straight going cars on the main road. That is to say, the effect of merging vehicles on the headway distribution of main roads was not taken into account.

4.2 Determination of the variable critical gap t_c

The critical gap which was chosen by merging drivers will be influenced by many factors, such as the main road traffic flow, the characteristic of drivers and vehicles and the driving vision. This paper assumes that all drivers are homogeneous and will make the same choice for merging under the same condition. Kita[8] has shown that the drivers' merging critical gap will be changed in different positions of acceleration lanes and the value decreases with travel distance increase. Drivers usually estimate a safe gap for merge when first arriving at the beginning of acceleration lanes, and this gap is defined as the initial critical gap. And the driver will make a decision to merge if the headway between two major road vehicles is bigger than this value. Otherwise, he or she will travel through the acceleration lane to wait for the secondary coming gap and judged again. When drivers travel along the acceleration lane of an on-ramp, the closer the drivers are to the end of the acceleration lane, the stronger they would be anxious about