SAFETY-BASED CAPACITY ANALYSIS FOR CHINESE HIGHWAYS
– A Preliminary Study –

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Many years of research have led to the development of theories and methodologies in roadway capacity analysis in the developed countries. However, those resources coexist with roadway design and traffic control practices in the local country, and cannot be simply transferred to China for applications. For example, the Highway Capacity Manual in the United States describes roadway capacity under ideal conditions and estimates practical capacities under prevailing conditions in the field. This capacity and the conditions for change are expected to be different on Chinese roadways as the local roadway design (lane width, curves and grades), vehicle size, and traffic mix are different. This research looks into a different approach to the capacity issue different from the Highway Capacity Manual. According to the car-following principle, this paper first describes the safety criteria that affect traffic operations. Several speed schemes are subsequently discussed as they are affected by the maximum speed achievable under the local conditions. The study has shown that the effect of geometric and traffic conditions can be effectively reflected in the maximum speed adopted by the drivers. For most Chinese highways without a posted speed limit, the choice of speed by the drivers from the safety prospective is believed to have incorporated considerations of the practical driving conditions. Based on this, a condition for capacity calculation is obtained by comparing the desired vs. safety-based distance headways. The formulations of the model are mathematically sound and physically meaningful, and preliminary testing of the model is encouraging. Future research includes field data acquisition for calibration and adjustment, and model testing on Chinese highways.

Key Words: Practical capacity, Free-flow speed, Minimum distance headway, Desired distance headway

1. INTRODUCTION

The sustained economic growth in China in recent years has brought opportunities and challenges to the planning and management of the Chinese transportation system. Like in other developing countries, the transportation system in China is characterized by limited roadway infrastructure and the lack of operation and management experience. Among the most critical issues in traffic planning and management is to determine the capacities of Chinese highways.

Many years of research have led to the development of theories and methodologies in roadway capacity analysis in developed countries. However, those resources coexist with the roadway design and traffic control practices in the local country, and cannot be simply transferred to China for applications. For example, the Highway Capacity Manual in the United States describes roadway capacity under ideal conditions and then estimates practical capacities under prevailing conditions in the field. This capacity and the conditions for adjustment are expected to be different on Chinese roadways as the local roadway design (lane width, curves and grades), vehicle size, and traffic mix are different. Because there is not a systematic approach to this problem, coupled by a lack of fundamental data, the adjustment factors from the Highway Capacity Manual cannot be easily revised and applied to Chinese highways.

This research looks into a different approach to the capacity issue from the Highway Capacity Manual. According to the car-following principle, this paper first describes the safety criteria that affect traffic operation, then proposes a condition for capacity calculation by comparing the desired vs. safety-based distance headways. Using the proposed formulations, a preliminary test is presented to illustrate the implementation of the model. Finally, discussions are made before the study is concluded.
2. HIGHWAY CAPACITY

The capacity of a highway can be analyzed in a number of ways, including the empirical approach and the theoretical approach. Among them, the Highway Capacity Manual method is the most widely used in the United States, and it has started to find its applications in other countries such as China and India. The theoretical method is used mostly in analytical studies with a known relationship between traffic flow, density, and speed.

The HCM method consists of three major steps. The first step is to find the capacity of highway facilities under ideal conditions. Second, the levels of service are selected to represent different operating qualities and to determine the maximum flow rates under these different levels of service. Finally, adjustment factors due to prevailing roadway and traffic conditions are applied to the ideal conditions to obtain the maximum flow rates at different levels of service.

A basic capacity is determined based on the repeatedly observed maximum traffic flow under ideal traffic and geometric conditions. Because the roadway, traffic, and control conditions vary from one location to another, the prevailing capacity for a highway segment is determined by multiplying the ideal capacity by the adjustment factors in Highway Capacity Manual (HCM). For any segment of highways operating under non-ideal conditions, its practical capacity will normally be smaller than the basic capacity. Thus,

\[ C_p = C \times \prod f_j \] .......................................... (1)

where \( C_p \) = practical capacity
\( C \) = basic capacity
\( f_j \) = adjustment factor for the condition \( j \).

The theoretical method of capacity analysis is mainly based on the traffic flow theory which is developed according to the principles of fluid flow. In a theoretical formulation, the flow rate is generally a function of density or speed with a maximum value at the convex shape of a curve\(^2\). The maximum flow rate may be determined on the flow-speed or flow-density curve. Theoretically, this maximum point represents the capacity.

None of the existing capacity analysis methods can be readily used on Chinese highways because of the different traffic and geometric conditions in China. Although the HCM method is simple to apply, the corresponding “ideal conditions” as defined in the method have not been identified for Chinese highways which are usually characterized by narrower lanes and shoulders, shorter entrance and exit ramps, and relatively larger speed differentials among the motor vehicles. In addition, there lacks a systematic approach and a large quantity of operation data to support any effort to develop adjustment factors following the HCM approach.

Although traffic flows on Chinese highways are analogous to fluid flows, the limitations of the existing theoretical models must be strengthened before any application may be attempted. Generally, a theoretical capacity may not reflect reality; thus, it may not be used in the real situations. To use this value as the capacity in planning analysis and traffic control, it is essential to know whether this maximum flow rate reasonably reflects travel conditions and addresses the highway safety requirements. Since the determination of the maximum flow rate on a theoretical model is purely mathematical, the result often overestimates or underestimates the practical capacity. This limitation has resulted in a heavy dependence on the field observations for capacity estimation. With the lack of theoretical guidance and field data on Chinese highways, such an analysis will always have to build in many uncertainties.

In an attempt to promote Chinese highway capacity research and improve the aforementioned limitations, we proposed in this paper an analysis method based on the car-following principle and traffic safety considerations. We believe that the effects of roadway conditions, traffic control, and the driving behaviors of the motorists influence the maximum running speed. The choice of speed by drivers from safety prospective is believed to have incorporated considerations of the practical driving conditions. For most drivers, it is the car-following safety criteria they first consider when selecting the travel speed, and they always try to maximize the safe travel speed to reach the capacity.

In the next sections we will discuss the safety-based driving conditions, and propose the capacity analysis method. Limited field observations and verifications have also been included.

3. ANALYSIS OF DISTANCE HEADWAY

The distance headway and speed of traffic stream directly determine the capacity. Generally speaking, as the flow rate increases traffic speed decreases. Recent studies\(^3\) showed that when traffic is light, the change in
speed is very limited; as the flow rate approaches the capacity, the speed reduction is more obvious and then the only way to increase the traffic throughput is to reduce the distance headway. The distance headway near capacity is determined and collectively adopted by the driving population, with a perceived balance of the minimum headway and the desired headway. The minimum headway is needed for safe stopping of a vehicle whereas the desired headway is selected in order to achieve the best flow rate (perceived perhaps as having minimum delay). The feasible range for speed and distance headway can be illustrated by the speed-distance diagram shown in Figure 1, where $s_0$ represents the minimum distance headway (minimum spacing), i.e., a vehicle’s physical dimension plus the minimum gap between two vehicles, and $v_f$ is the free-flow speed. Generally, the distance headway increases as the speed increases. The points on the vertical axis represent the stop condition with different densities, while the points on the diagonal line from $s_0$ represent the safety requirement. The shaded area represents a feasible region for speed and distance headway. Below the feasible region, the points (below the diagonal boundary line) represent risky operations.

$$d_g = s_0 + v\delta + v^2\phi$$ ......................................................... (2)

where $s_0$: minimum spacing between two successive vehicles at jam condition, meter

$\delta$: perception-reaction time, sec
$\phi$: desired deceleration factor of the leading and following vehicles, $sec^2/m$.

The safe distance headway varies with the speed and deceleration rates of the leading and following vehicles. In the extreme case, if the leading vehicle stops instantly ($\phi$ is maximum) a large $d_g$ is then required in order to provide sufficient stopping distance. If the deceleration rates of both vehicles are the same, only the first two terms in Equation (2) will remain, which derives the minimum distance headway, as

$$d_{min} = s_0 + v\delta$$ ......................................................... (3)

The minimum distance headway provides the safety criteria under the two operating situations. The degree of safety increases as the required distance headway increases from the minimum distance headway in Equation (3), to the general distance headway in Equation (2). When the driver’s desired distance headway meets the safety requirement, the measured distance headways in the field are more evenly distributed (with a small standard deviation) and the traffic flow is stable at or close to the equilibrium state. Therefore, it is important to estimate correctly the roadway capacity in order to implement proper freeway mainline and ramp control, and avoid unstable flow and the consequent congestion.

According to the car-following theory, under prevailing travel conditions, the theoretical roadway capacity is calculated as:

$$q = \frac{v}{s}$$ .................................................................................. (4)

$$s = s_0 + v\delta + v^2\phi$$ ......................................................... (5)

where $q$: flow rate, veh/sec;
$v$: travel speed, m/sec;
$s$: safe stopping distance, m;
$s_0, \delta, \phi$: defined earlier.

Therefore, flow rate is a function of speed, and

$$q = \frac{v}{s_0 + v\delta + v^2\phi}$$ ......................................................... (6)

The maximum flow rate and the capacity can be obtained by:

$$v_m = \frac{s_0}{2\sqrt{\phi}}$$ ......................................................... (7)

$$C = \frac{3600}{2.121\sqrt{s_0\phi} + \delta}$$ ......................................................... (8)
where $C$ is the capacity and $v_m$ the corresponding speed of the traffic stream. It should be noted that the perception time does not affect the travel speed under capacity.

### 3.2 Desired distance headway

To drive efficiently and comfortably, drivers have their own desired distance headway ($d_d$) based on highway geometry and traffic conditions. Under a stable traffic flow, the desired distance headway follows the one defined by the traffic flow model which can be calibrated from local data. In other words, if such a model can be obtained, the desired distance headway is obtained. Unfortunately, many of the proposed models such as Greenshields$^2$, Greenberg$^5$, and Underwood$^6$, etc., are not supported by recent field data$^{1,7,8}$.

According to the nonlinear follow-the-leader traffic modeling$^9$, the Bell-shaped curve is a formulation capable of describing the fundamental relationship among flow rate, density, and speed as exemplified in recent field data$^{1,10,11}$. This model also has a relatively simple mathematical form for calibration from local conditions. According to the Bell-shaped curve model, traffic flow and density can be expressed as:

$$k = \sqrt{2k_m\ln(v_f/v)} \quad \text{.................................................. (9)}$$

$$q = \sqrt{2v_km\ln(v_f/v)} \quad \text{.................................................. (10)}$$

where $k_m$: the density at the point where the capacity is reached;

$v$: travel speed, mph;

$k$: density, veh/mile;

$v_f$: free-flow speed, mile/hr.

When, $k = \frac{1}{d_d}$, $k_j = \frac{1}{s_0}$, and $k_m = \frac{1}{2.586s_0}$ (solvable from maximum flow condition), the desired distance headway is obtained:

$$d_d = \frac{1.8286s_0}{\sqrt{\ln(v_f/v)}} \quad \text{.................................................. (11)}$$

In Figure 2, it can be seen that with the increase of speed, the distance headway increases monotonously. The curve representing the desired distance headway defined by Equation (11) intersects the minimum distance headway curve by Equation (3) at speed $v_p$. It can also be seen that when $v > v_p$, the desired curve is above the curve of minimum distance headway, and when $v < v_p$, the desired distance headway curve is below the minimum distance headway. This indicates that when the traffic conditions is good and speed is large, motorists are concerned more about comfort and ease of travel, and the safety headway requirement is not in conflict with their desires. However, when traffic becomes heavy and the mobility is constrained gradually, the demand for efficiency may involuntarily overweigh safety and the desired distance

![Fig. 2 The desired distance headway vs. minimum distance headway with FFS = 65mph](image-url)
headway could drop in the risky region. This explains why there are more accidents (head-on, rear-end, side-swipe, etc.) when the flow rate is heavy.

Notice that, in Equations (2) and (3), the safety-based distance headways are independent of the free-flow speed \( v_f \), while the desired distance headway is a function of the free-flow speed. As the free-flow speed decreases, the curve representing the desired distance headway moves leftward in Figure 2. A higher free-flow speed could result in a larger portion of the desired distance headway positioned below the curve of the minimum distance headway.

Let Equation (3) equal Equation (11), we can define a condition for stable traffic flow and safe and efficient operation. When both the desired and minimum distance headways are equal, speed \( v_p \) can be calculated thought this equation:

\[
s_0 + v_p \delta = \frac{1.8286 s_0}{\ln(v_f/v)} \tag{12}
\]

Because Equation (12) is transcendental, there is no analytical solution. Therefore, we used a numerical approach through simulation to find a simplified mathematical form of \( v_p \), and found the following expression that closely resembles Equation (13) in the meaningful range of its model parameters:

\[
v_p = (0.423 + 0.00354 v_f + 0.12 \delta + 0.00299 s_0 - 0.000023 s_0) v_f \tag{13}
\]

where \( v_f \) : free-flow speed, mph;
\( \delta \) : perception-reaction time, sec;
\( s_0 \) : minimum spacing between two connective vehicles, ft.

4. DETERMINATION OF CAPACITY

Due to variations in roadway design standards and lack of operation data, it is nearly impossible at the present time to define an ideal operating condition for Chinese highways as that in the HCM. Instead, the application of the desired vs. minimum distance headway conditions represents a feasible way to estimate capacity estimate.

Assuming that for a given highway section the free-flow speed is \( v_f \), and the desired distance headway can be obtained after calibration of the Bell-shaped curve model from data, the relationship between speed and flow rate can be shown in Figure 3. The maximum flow rate is often considered at point \( m \), which is defined as the capacity under the given condition. However, if this point is above the minimum distance headway curve (shown in the figure), this capacity represents an unsafe traffic state as discussed previously. It is risky and not practical to use this value as the capacity.

Therefore, the practical capacity is the maximum flow rate that meets the safety headway requirement as
well as the desired distance headway requirement under the prevailing travel conditions. According to this definition, the maximum flow rate is at point \( p \) in Figure 3 and it should be considered as the practical capacity for the roadway section at a corresponding speed of \( v_p \). Before point \( p \), the flow rate should be computed on the premise of the minimum distance headway; after point \( p \), the flow rate should be computed to satisfy the Bell-shaped curve that is calibrated with field data. In the latter case, motorists select a comfortable headway already meeting the safety requirement so that the minimum distance condition no longer applies.

It should be pointed out that in most capacity modeling today, the safety headway requirement is not taken into account during the model calibration and parameter estimation. This may partly explain why we often experience problems on roadways carrying less traffic than the perceived capacity.

In the case of the minimum distance headway, the density \( k_{mdh} \) and flow rate \( q_{mdh} \) are:

\[
k_{mdh} = \frac{1}{s_0 + v \delta} \quad \text{(14)}
\]

\[
q_{mdh} = \frac{v}{s_0 + v \delta} = \frac{s_0}{v \delta} + \frac{1}{s_0} \quad \text{(15)}
\]

Once the desired distance headway becomes smaller than the minimum distance headway, such as in the range of \([0, k_p]\) in Figure 3 and the entire density range \([0, k_j]\) in Figure 4, the flow rate and speed will be determined by:

\[
v = v_f e^{-\alpha z} \quad (\alpha = \frac{1}{2k_m}) \quad \text{(16)}
\]

\[
q = \sqrt{2v km} \sqrt{\ln(v_f/v)} \quad \text{(17)}
\]

Combining the above discussions, the practical capacity of a roadway section can be determined as:

\[
C_p = \frac{1}{\frac{s_0}{v_p} + \delta} = \frac{3600}{\frac{s_0[m]}{v_p[m/sec] + \delta[sec]}} \quad \text{[veh/hr]},
\]

when \( v_p > v_m \) \quad \text{(18)}

or

\[
C_p = \frac{1}{\sqrt{e}}v_f km = 0.2345v_f k_j = 844.2 \frac{v_f[m/sec]}{s_0[m]} \quad \text{[veh/hr/ln]},
\]

when \( v_p < v_m \) \quad \text{(19)}

As an illustration of \( C_p \) computation, assume the minimum distance headway \( s_0 = 6m \) (20 ft), free-flow speed \( v_f = 30m/sec \) (65mph), perception reaction time \( \delta = 1.5 \) sec. In Figure 3, \( v_p = 24m/sec \) (54mph), \( v_m = 18.7 \) m/sec (40mph). Since \( v_p > v_m \), the capacity is:

\[
C_p = \frac{3600}{\frac{6}{24} + 1.5} = 2057 \text{veh/hr}
\]

![Fig. 4 The relationship of flow rate vs. speed with FFS = 35MPH](image)
5. PRELIMINARY FIELD TESTING

Since data from Chinese highways are not available at this time, we conducted a preliminary test of the model on a local freeway. Several speed studies were conducted on Route 8 in Akron, Ohio. Route 8 runs in the north and south direction and it connects the City of Akron to the City of Cleveland. There are two lanes in each direction with a narrow shoulder width, which provides a valuable case to observe the change in the free-flow speed due to less ideal conditions. We used a laser speed measuring system to obtain travel speed with a very high precision. Two surveys were conducted in October, 2003, from 10:15 AM to 11:45 AM when traffic was light. In Table 1, we show some sample data from the survey study. Un-

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Mean S.D. Mean S.D. Mean S.D. Mean S.D.
57.29 0.55 52.21 0.69 56.35 0.57 50.60 0.54

*: In HCM 2000, FFS is measured using the mean speed of passenger cars operating in low-to-moderate flow conditions (up to 1,400 pc/hr/ln). Mean speed is virtually constant across this range of flow rates.
der the current condition, the free-flow speed of the left lane (passing lane or fast speed lane) is greater than that of the right lane. The free-flow speed for the two northbound lanes is 52 mph (84 km/hr) and 57 mph (90 km/hr), and for the southbound traffic is 50 mph (80 km/hr) and 57 mph (90 km/hr), respectively.

We also conducted traffic counts during the PM peak hour from 4:55 PM to 5:10 PM. The traffic flow was very heavy, but stable without congestion. Based on our field observation and data analysis, the roadway is running at capacity during this time of the day. Using a Jamar counter, the flow rate was measured as 2032 veh/hr for left lane, 1848 veh/hr for right lane of the northbound traffic. By collecting the afternoon data, we wanted to test if the proposed method can be applied to traffic under non-ideal conditions, and if the measure data support the numerical results of the mathematical computations from the model.

According to Equation (13), with \( s_0 = 20 \text{ ft} (6\text{ m}) \), \( \delta = 1.5 \text{ seconds} \), \( v_f = 52 \text{ mph (84 km/hr)} \)

\[
v_f = \left(0.423 + 0.00354 \times 52 + 0.12 \times 1.5 + 0.00299 \times 20 - 0.000023 \times 20^2 \right) \times 52 = 43.6 \text{ mph} = 19 \text{ m/sec}
\]

\[
v_m = \frac{v_f}{\sqrt{e}} = \frac{52}{\sqrt{e}} = 31.5 \text{ mph}
\]

Since \( v_p > v_m \), therefore,

\[
C_P = \frac{1}{s_0 + \delta} = \frac{3600}{6 + 1.5} = 1982 \text{ [veh/hr]}
\]

The calculated flow rate, 1982 vph, is close to the field measured value, 2032 vph. The distance headway conditions are also summarized in Figures 5 and 6.

6. CONCLUSIONS

This paper presents a method for capacity estimation for Chinese highways. The existing problem in capacity analysis in China is that there is no established procedure comparable to the HCM of the United States. In addition, the lack of operation data also hinders the effort of researchers and engineers to develop practical capacity models suitable for Chinese roadways and traffic conditions. The method for capacity analysis presented in this paper combines the issues of the safety criteria and car-following principles. The underlining premise of this method is the postulation that the effects of roadway conditions, traffic control, and the driving behaviors of the motorists influence the maximum running speed, and that
the choice of free-flow speed by drivers is believed to have incorporated considerations of the practical driving conditions from the prospective safety.

The theoretical derivations described in the paper have shown that when determining roadway capacities, the relationship between the desired distance headway and the minimum distance headway is critical as it affects the estimated capacity. Erroneous estimates especially from overestimation can lead to unstable flow and traffic congestion. For safe operation, the desired distance headway must be larger than the minimum distance headway. When the two headways are both satisfied, the maximum flow rate can be reached.

The preliminary field test study has shown that geometric conditions can effectively reduce the maximum speed selected by drivers both in free-flow and heavy-flow conditions. The limited testing results seem to support the merit of the proposed method. As much as we will try to improve the modeling of this method, we plan to test and evaluate its effectiveness with data from Chinese highways. Work is already underway by our collaborating Tsinghua University to collect data from the beltways in Beijing.

We are cautiously optimistic to point out that since the formulations in the model do not require identification of ideal vs. prevailing conditions, the method may even be extendable to U.S. highways with extreme geometric conditions and driving conditions not adequately covered by the HCM. Such conditions may include work zones, roadways with above-normal curvatures or slopes, etc.

REFERENCES