The Development and Practice of China Highway Capacity Research

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Abstract
The achievements of the project “highway capacity research” in the "9th Five-Year" period in China have supported the current "Technical Standard of Highway Engineering" and "Design Specification for Highway Alignment", which are the most important specifications for the design and construction of highway in China and guidance of the construction and operation of tens of thousands of kilometers of highway. At present, China's highway industry is still in a period of rapid development. By the end of 2014, the total mileages of highway network exceeds 4,400,000 kilometers, of which the freeway’s mileage reaches 112,000 kilometers. With this rapid development of highway system, since the “9th Five-Year”, the highway capacity research in China is still ongoing.

This paper provides a brief introduction of research history, on-going research and future work of highway capacity research and application in China. According to the paper, four major stages of highway capacity research in China are proposed. Stage 1 (before 1990) is called the beginning stage. Stage 2 (1991-2000) is extensive research stage, in which large-scale research was conducted based on the foreign advanced practical experience, such as USA’s. Stage 3 (2001-2010) is in-depth focus on important facilities, and stage 4 (2011 till now) is the adjustment and updating of achievements stage. The paper also introduces the representative research projects and achievements of each stage. Besides, the paper also presents the current achievements of China Highway Capacity Manual (CHCM) which is still in draft. The structure of the manual as well as the newly added contents such as the capacity analysis of work zone is introduced. The paper mainly introduces the achievements of the chapter about basic expressway section in CHCM, which include the new speed – volume relationship on freeway, the level of service index and classification, and vehicle classification and equivalent coefficients as well as capacity analysis procedure and method. Finally, the paper introduces the prospect of future direction of capacity research in China, such as traffic characteristics and dynamic change of capacity under huge volume with free passage in holidays etc.

Keywords: Highway Capacity, Speed/Flow relationship, Level of Service (LOS)
1 Development of Highway Transportation in China

In recent years, China has made remarkable achievements in highway construction, which has greatly promoted the incensement of road transportation. By the end of 2014, the total mileage of highways in China had already reached 4.46 million kilometers, while the mileage of freeways has reached 112,000 kilometers, as shown in Figure 1. Highway network, which takes the freeways as the framework, the other highways as the main body, has been formed. In the blueprint of “National Highway Network Planning (2013-2030)”, the total size of the highway network will be 5.8 million kilometers, in which the mileage of national freeways is about 118,000 kilometers, mainly consisting of 7 radiation lines from Beijing, 11 north-south bound lines, 18 east-west bound lines, as well as regional ring roads, frontage lines, and connecting roads, etc. Besides the rapid development of road network, China’s current motor vehicle population has reached 260 million, and number of motor vehicle drivers has reached 250 million, as shown in Figure 2. Therefore, China is experiencing the stage of rapid development. Accompanied by the development of China’s highway construction and motorization, the research and practice of highway capacity is continuously developing and enhancing.

![Figure 1: Mileages of highway and freeway (data of rural road has included since 2006)](image1)

![Figure 2: Population of motor vehicles and drivers](image2)
2 Historical Contexts for Capacity Research

This section presents a summary of the capacity research progress undertaken at the ministry of transport, universities as well as transport department and design institute of some provinces. Compared with the United States and other developed countries, China’s highway capacity research started late, which was directly caused by the late construction of high grade highways and motorization. Generally, China’s highway capacity research is divided into 4 stages, which are introduced respectively in the following sub-sections.

2.1 Research before 1990’s

The first stage of highway capacity research is before 1990. At that time, there was no freeway in China. Therefore, research of highway capacity of China was conducted by studying and following the highway capacity research abroad, especially the research of United States, such as Highway Capacity Manual (HCM) 1985. The basic method of the research was using the measured data to study the analysis method of capacity and level of service which was suitable for China. However, these studies were few and scattered, and could not form the core theory and framework of highway capacity analysis in China. The research mainly focused on the mixed traffic of two-lane highway (Zhang et al. 1987), intersection, and traffic flow theory (He, 1986), etc. The typical research is as follows:

(1) “Typical Signal-Controlled Intersection Capacity Analysis,” which was hosted by Beijing University of Technology, 1982.

(2) “Roundabout Capacity Analysis Using Gap Acceptance Theory,” which was hosted by Southeast University.

(3) “Small Roundabout Capacity Analysis,” which was hosted by Chang’an University.

(4) “Design Capacity Analysis on Mixed-Traffic Two-Lane Highway Section,” which was hosted by Research Institute of Highway (RIOH), Ministry of Transport, and supported by 5 provinces and 1 city. This project provided a reasonable and practical method for capacity analysis, but was poor on transferability.

2.2 Research in the 1990’s

From 1991 to 2000, the highway capacity research in China entered the extensive research stage. During that period, with the rapid development of freeway construction in China, research on highway capacity and traffic flow theory was highly demanded because of the road construction. The major work in this stage included systematic study of the HCM of the United States, and conduction of the capacity research for each existing highway facility, which significantly contributed to the formation of China’s capacity analysis method system (Cai, 1992; Chen, 1997; Zhou et al, 1998) . The typical research is as follows:

(1) “Translation of HCM 85 of United States,” which was hosted by Beijing University of Technology, 1991.

(2) “Standard of Generalized Daily Service Volumes and Vehicle Conversion Factors for Different Grade Highway,” which was hosted by Research Institute of Highway (RIOH), Ministry of Transport, 1994. The achievements of this research have been involved in related highway technology standards, and were applied as the foundation of highway division.

(3) “Road Capacity Research for Hinterland in Central Plains,” which was sponsored by World Bank and applied in Hebei and Henan Provinces, 1995 (Feng, 1994).

(4) “Highway Capacity Research,” which was the national key scientific and technological research project during the “9th Five-Year”, and hosted by Research Institute of Highway (RIOH), Ministry of Transport, 1996.
In this stage, the most comprehensive and systematic project is the “Highway Capacity Research.” This project took five years, and had obtained rich achievements: a) development of the traffic flow automatic testing system and data statistical analysis software; b) establishment of the speed-flow statistical analysis model for highway section of representative areas in China; c) systematic construction of the traffic simulation models for freeways and two-lane highways for the first time, which could well describe the traffic characteristics of China, and developed related software; and d) provision of the highway capacity analysis method which suited to China’s national conditions. These achievements listed above strongly supported several critical national standards, such as “Technical Standard of Highway Engineering.” The accomplishments of this project generally reached the international advanced level, and won the second prize of national scientific and technological progress.

2.3 Research in the 2000’s

From 2001 to 2010, research of highway capacity entered improvement stage. In this stage, Chinese government and related departments have sponsored a lot of projects to improve the highway capacity research. For example, the research on two-lane highway capacity in mountainous area was conducted in this stage, in order to improve the achievements of two-lane highway capacity of plain area which was obtained during “9th Five-Year.” Besides, the focus of capacity research has gradually shifted from highway system to urban road system, especially to the urban expressway system. Generally, the typical projects focused on the freeways and urban road are as follows:

(1) “Expressway System Capacity Research,” which was the national key scientific and technological research project during the “9th Five-Year,” and was hosted by RIOH, 2002. This project obtained the following critical achievements: a) the speed-flow statistical analysis model for expressway system was established; b) the theoretical analysis system of the expressway capacity, which was suitable for China’s national condition, was proposed for the first time in China, and the ideal capacity values for each component of the expressway such as basic section, weaving section, and merging and diverging section were determined; c) the weaving section was classified, and its capacity estimating method based on the gap acceptance theory and optimization theory was built; and d) traffic simulation models for expressway system was developed, and “Guide for Expressway Capacity Analysis” was published. All these achievements effectively supported several industrial standards such as “Specification for Design of Urban Expressway” (CJ129-2009) (Industry Standard of the People’s Republic of China, 2009) and “Code for Design of Urban Road Engineering” (CJJ37-2012) (Industry Standard of the People’s Republic of China, 2012).

(2) “Traffic Flow Theory and Its Application in Urban Expressway System,” which was sponsored by National Science Foundation and was hosted by Harbin Institute of Technology, 2003.

(3) “Two-Lane Highway Capacity Research in Mountain Area,” which was sponsored by Ministry of Transport and was hosted by RIOH, 2003.

(4) “Research on Urban Road Capacity and Traffic System Evaluation Method,” which was sponsored by national science and technology support program and was hosted by Beijing University of Technology, 2006.

(5) “Research on Capacity of Highway Construction Area,” which was hosted by RIOH, 2007.

(6) “Translation of HCM 2000 of United States,” which was hosted by Beijing University of Technology, 2007.

(7) “Capacity Research of Urban Expressway Interchange,” which was hosted by RIOH, 2008.

All these achievements in this stage supported the latest versions of China’s highway and urban road standards and specifications, such as “Technical Standard of Highway Engineering”, “Design Specification for Highway Alignment”, “Specification for Design of Urban Expressway”, and “Code for Design of Urban Road Engineering.” Moreover, these achievements have laid a very important theoretical and practical foundation for the development of traffic engineering discipline, and have
helped to upgrade the research level of several research institutes and universities, such as RIOH, Beijing University of Technology, Southeast University, and Tongji University, etc.

2.4 Research after the 2010

From 2011 to now, the research of capacity enters a new promotion stage. In this stage, more attention is paid to practical application of the capacity analysis and the correction of related influence coefficients in capacity analysis. Currently, the capacity of road network and the improvement of the traffic efficiency are the two research hotspots. The typical research projects are as follows:

1. “Traffic Impact Assessment of Highway Network in Disaster Weather,” 2010.
2. Study on Mobility Classification of Road Network in “Technical Requirements for Monitoring and Service of Highway Network,” 2011.
3. “Operation Plan of Construction and Maintenance Based on Optimization of Road Network Traffic Situation,” 2012.
4. “China Highway Capacity Manual,” which is hosted by RIOH, 2012. More introductions will be provided in coming section.

3 Current Practice: China Highway Capacity Manual (CHCM)

Until now, China has no official version of HCM, although capacity analysis methods for several highway facilities are well improved and are involved in related standards to guide the construction of tens of thousands of kilometers of highway (Industry Standard of the People’s Republic of China, 2006, 2014). From the year of 2012, RIOH started to develop CHCM (Highway Bureau of MOT, 2015). Currently, this work has almost been completed, and CHCM is expected to be officially published in 2016. The general principle of CHCM development is “based on the current situation, make the key points stand out, and focus on practical.” The developing methods are as follows: a) summarizing existing researches; b) learning from HCM of other countries, such as HCM of United States, and HCM of German; and c) conducting the special investigations and studies for toll station, roundabouts and other facilities.

3.1 Structure of CHCM

The CHCM is divided into 13 chapters, which are showed as follows:

| No. | Chapter                        |
|-----|--------------------------------|
| 1   | general principles             |
| 2   | Terminology and symbols        |
| 3   | traffic characteristics        |
| 4   | Freeway basic section          |
| 5   | Weaving section                |
| 6   | Merging and diverging section  |
| 7   | Freeway work zone              |
| 8   | First class highway (multilane)|
| 9   | Second or third class highway (2-lane highway)|
| 10  | Non-signalized intersection    |
| 11  | roundabout                     |
| 12  | signalized intersection        |
| 13  | Toll station                   |

Table 1: Structure of CHCM
As shown in Table 1, CHCM has the following characteristics:

1. There are 5 chapters related to freeway: freeway basic section (Chapter 4), weaving section (Chapter 5), merging and diverging section (Chapter 6), freeway work zone (Chapter 7) and toll station (Chapter 13).

2. In Chapter 5, weaving section is divided into two types: one-sided weaving section and two-sided weaving section, and corresponding calculation formulas of each type are given.

3. In Chapter 6, the calculation procedure and method of the merging and diverging section are similar to the method in HCM 2000 of USA.

4. In view of the present situation of the freeway maintenance and reconstruction work zone, capacity analysis method of freeway work zone is provided as a separate chapter in CHCM. In this chapter, the basic capacity of work zone when one lane could be used is 1600pcu/h, while when two lanes could be used the capacity is 1950pcu/h. Besides the basic capacity, the reduction factors of the actual capacity, such as lane width, lateral clearance, speed limit, construction work intensity and light condition, are also given.

5. A new roundabout capacity estimation method is provided in CHCM. For this method, the capacity of roundabout is estimated by the capacity of each entry lane of the roundabout, which is affected by two aspects: the impact of geometric design of the entry lane and the impact of weaving traffic flow after vehicles enter the roundabout. For each type of impact, a capacity estimate model is established and the capacity value of entry lane could be estimated. The final capacity value of entry lane takes the minimum of the capacity values estimated by those two models.

6. In terms of the capacity analysis of toll station, CHCM provides not only the capacity estimate method of the general toll lane, but also added analysis and evaluation of the capacity and level of service of weight-calculating toll lane and ETC lane.

### 3.2 Introduction of main chapters: taking the basic section of freeway as example

Taking the basic section of freeway as example, this section focuses on the following contents of CHCM: speed-flow relationship, level of service (LOS), vehicle classification and conversion factors, capacity analysis method of basic section.

#### 3.2.1. Speed-flow relationship

As the most important theory for the traffic capacity research, speed-flow relationship is the critical basis for determining the value of the basic traffic capacity and level of service. Moreover, it is also the comprehensive reflection of road environment, vehicle characteristics and driving behavior.

In the 1990’s, according to the traffic situation of the time, typical speed-flow relationship based on observed data was given by “Highway Capacity Research” which was the national key scientific and technological research project during the “9th Five-Year” and is shown in Figure 3. At that time, total amount of freeways in China were no more than 10, and were not in the state of saturation. Besides, traffic compositions of these freeways are very complex. Therefore, it could be observed in Figure 3 that: (1) the free-flow-speed is very low; (2) at the same flow rate, there is a wide range of speed distribution; (3) basic capacity is small, and the speed-at-capacity is very low with 40-60km/h.
In view of the above characteristics, quadratic curves are used to describe the speed-flow relationships with different design speed under basic condition. Because most of observed freeways cannot reach saturated conditions, and it is difficult to predict the capacity, the recommended curves of speed-flow relationship are shown in Figure 4 which is based on traffic simulation analysis as well as the speed-volume relationship derived from on-site observed data as in Figure 3.

Currently, the typical speed-flow relationship of freeway with observed data is shown in Figure 5. Compared with Figure 4, a huge difference in traffic characteristics could be observed in Figure 5: (1) when traffic flow is less than 1000pcu/h, the trend of speed is very flat. In other words, free-flow-speed could be observed in a wide range of traffic flow; (2) when traffic flow is more than 1000pcu/h, the speed begin to decline; (3) the speed-at-capacity is about 70-80km/h; (4) the speed of shoulder lane is 10km/h lower than that of median lane; and (5) the basic capacity is about 2200pcu/h.
Based on the above characteristics, the recommended speed-flow relationship of freeway under basic condition in CHCM is provided in Figure 6. Compared with Figure 4, the curve in Figure 6 is more close to the curve of HCM of USA. It indicates that after 20 years of rapid development of motorization, driver behaviors in freeways are more standardized and orderly.

3.2.2. Level of service (LOS)

In the research during the “9th Five-Year,” the classification of the freeway’s LOS was mainly based on the flow-density relationship which is shown in Figure 7, and took density as the indicator. The classification standards of LOS are shown in Table 2. Generally, there are 4 levels of service from Level 1 to Level 4. Besides, Level 4 is divided into 2 sublevels. Consequently, there are actually 5 levels of service, which correspond to free flow, upper bound of steady flow, steady flow, saturation flow, and forced flow under congestion respectively.
With the development of HCM related research, researchers found that the classification of LOS mentioned above is not suitable for today’s freeway system of China (Liu, 2006). For example, the range of density between the upper-bound and lower-bound is too large with the difference of 11 pcu/km. Therefore, it is considered to divide original Level 2 to two levels: new Level 2 and new Level 3. After refinement of LOS classification, more levels of service could be chosen as the target in the road planning and design. In terms of the operation situation analysis of freeways, the new classification of LOS with more levels could help to give a more accurate conclusion, and is especially convenient for the application of real-time intervention measures.

Consequently, LOS in CHCM is divided into 6 levels which are shown in Table 3. Considering that the degree of congestion and actual driving speed are the two most important aspects for freeway users, CHCM takes v/C ratio as the main indicator of LOS to measure the degree of congestion. One of the advantages of using v/C ratio as the main indicator is that it is a relative index, and v/C ratios of different facilities (such as freeway and other highway) could be compared. Besides, difference between the actual driving speed of small passenger cars and the free-flow-speed is applied as the secondary indicator of LOS. Speed variance can well reflect the influences of traffic composition on traffic flow. In the same v/C condition, operating speed of passenger cars will be relative low if truck volume is in high percentage.

| Level of Service | Density (pcu/km) |
|------------------|------------------|
| 1                | ≤7               |
| 2                | (7,18]           |
| 3                | (18,25]          |
| 4                | (25,45]          |
|                  | ≥45              |

Table 2: Classification standards of freeway’s LOS (takes density as the indicator)
### Table 3: Classification standards of LOS of freeway’s basic section

| LOS | Main Indicator | Secondary Indicator |
|-----|----------------|---------------------|
|     | v/C Ratio | Difference between the actual driving speed of small passenger cars and the free-flow-speed (km/h) |
| A1  | ≤10       |                     |
| A   | A2 0.35   | 10–20               |
|     | A3 >20    |                     |
| B   | B1 ≤10    |                     |
|     | B2 0.35<v/C≤0.55 | 10–20           |
|     | B3 >20    |                     |
|     | C1 ≤20    |                     |
|     | C2 0.55<v/C≤0.75 | 20–30           |
|     | C3 >30    |                     |
|     | D1 ≤20    |                     |
|     | D2 0.75<v/C≤0.90 | 20–35           |
|     | D3 >35    |                     |
|     | E1 ≤30    |                     |
|     | E2 0.90<v/C≤1.00 | 30–40           |
|     | E3 >40    |                     |
| F   | v/C>1.00  |                     |

**Table 3:** Classification standards of LOS of freeway’s basic section

### 3.2.3. Vehicle classification and conversion factors

In earlier research during the “9th Five-Year,” vehicles were classified into 4 categories. The vehicle classification and conversion factors are shown in Table 4.

| Vehicle Types   | Conversion Factors | Description |
|-----------------|--------------------|-------------|
| Cars            | 1.0                | passenger cars with seats not more than 19 or trucks with loads not heavier than 2 tons |
| Medium vehicle  | 1.5                | passenger vehicles with seats more than 19 or trucks with loads between 2 and 7 tons |
| Large vehicle   | 2.0                | Trucks with loads between 7 and 14 tons |
| Trailer         | 3.0                | Trucks with loads heavier than 14 tons |

**Table 4:** Vehicle classification and conversion factors in earlier researches during the “9th Five-Year”

With the development of traffic and transportation in China, the traffic environment and operation characteristics have changed a lot, which lead to the unsuitability of the original vehicle conversion factors. The critical problems using these conversion factors are as follows:

(1) Several local traffic management departments consider that original conversion factors of large vehicle and trailer are too small. They suggest that it is more appropriate to add 0.5 or 1.0 on these original conversion factors.

(2) A small number of local traffic management departments consider that the original conversion factor is not appropriate in the case of the vertical slope is greater than 3%.

(3) The original conversion factor has been used for nearly 15 years. However, the proportion of trucks, vehicle types and load of vehicle have changed a lot in these years, and more types of trucks which are heavier than 14t are running on the highway. Under this situation, the equivalent volume of car estimated by the original conversion factors is much smaller.

Considering the vehicle contour dimension, power weight ratio and driving space, CHCM has updated the vehicle classification and corresponding conversion factors, which are shown in Table 5.
| Vehicle Types       | Conversion Factors | Description                                                                 |
|--------------------|--------------------|-----------------------------------------------------------------------------|
|                    | Plain area        | Mountain Area                                                              |
| Cars               | 1.0                | 1.0 passenger cars with seats not more than 19 or trucks with loads not heavier than 2 tons |
| Medium vehicle     | 1.5                | 2.0 passenger vehicles with seats more than 19 or trucks with loads between 2 and 7 tons |
| Large vehicle      | 2.0                | 3.5 Trucks with loads between 7 and 20 tons                                 |
| Trailer            | 3.0                | 5.0 Trucks with loads heavier than 20 tons                                   |

Table 5: Vehicle classification and conversion factors in CHCM

3.2.4. Capacity analysis method

Similar to the HCM2000 of USA, the capacity analysis of basic section is conducted by free-flow speed correction.

As shown below is the calculation steps of LOS of basic section, which is similar as that of US HCM, the actual capacity value can be determined by Figure 6 or interpolating from table below.

| Base free-flow speed (km/h) | 110 | 100 | 90 | 80 |
|----------------------------|-----|-----|----|----|
| Base capacity [pcu/(h*ln)]  | 2200| 2100| 2000| 1800|

Table 6: Base capacity vs. base free-flow speed

The free-flow speed could be calculated by Equation (1). Subject to the limitations of the research data, the impact of the density of the interchanges on the free-flow speed is not considered.

\[ v_{FF} = v_{BFF} + \Delta v_e + \Delta v_N \]  

(1)
where $v_{FF}$ is the actual free-flow speed of the basic section of freeway (km/h), $v_{BFF}$ is the basic free-flow speed of this basic section (km/h), $\Delta v_w$ is the correction of the basic free-flow speed considering the impact of lane width and the width of roadsides (km/h), and $\Delta v_N$ is the correction of the basic free-flow speed considering the impact of number of lanes (km/h).

4 Future Directions of Research

Through the research and practices of the past 30 years, highway capacity analysis of China has obtained lots of achievements, while many of those have been involved into Specifications and provide a better guidance for the construction and management of China’s highways. However, the research of highway capacity should be continuously improved and updated along with the development of highway traffic. In the future, more attention will be paid to the application of more extensive and real-time traffic data for more detailed and in-depth analysis, such as the capacity research on holidays with the toll-free policy for small passenger cars, the impact analysis of adverse weather and traffic incident on capacity, the research of capacity and reliability promotion of highway network, etc. For the CHCM, the coming work will involve the achievements of urban road’s capacity to current manual. In that case, the CHCM will have the chapters related to transit, pedestrians, non-motorized vehicles and facilities in transportation hub. Consequently, the CHCM will become a more comprehensive and instructive manual.

References

Cai, L.B. (1993). Traffic Characteristics of Two-Lane Two-Way Roads. Journal of Traffic Engineering in China, (1): 10-16.

Chen, J. Y. (1997). Integration of Traffic Microscopic Simulation and Macroscopic Simulation. Journal of Tongji University, 25(1): 46-49.

China Highway Capacity Manual, (2015). Beijing: Highway Bureau of MOT, China.

He, X.C. (1986). Development of Traffic Flow Break-down Model. Journal of Changsha Communications University, 2(1): 81-85.

Feng, G.Y. (1994). Characteristics of Entropy and Traffic Composition of Mixed Traffic. Journal of Hunan University, 19(2): 56-62.

Industry Standard of the People’s Republic of China (2006). Design Specification for Highway Alignment. (JTG D20-2006), Beijing: China Communication Press.

Industry Standard of the People’s Republic of China (2009). Specification for Design of Urban Expressway. (CJ129-2009), Beijing: China Architecture & Building Press.

Industry Standard of the People’s Republic of China (2012). Code for Design of Urban Road Engineering. (CJJ37-2012), Beijing: China Architecture & Building Press.

Industry Standard of the People’s Republic of China (2014). Technology Standard of Highway Engineering. (JTG B01-2014), Beijing: China Communication Press.

Liu, J. (2006). Research on two-lane highway capacity on mountainous area. Doctoral dissertation of Beijing University of Technology.

Research Institute of Highway Ministry of Transport and Beijing University of Technology (1994). Report of Design Traffic Volume and Passenger Car Equivalent Criteria on Highways, China.

Zhang, Z.Y., Xing H.C. and He, Y.F. (1987). Design Capacity of Mixed Traffic of Two-Lane Two-Way Road Sections. Beijing, Research Institute of Highway Ministry of Transport.

Zhou, R.G, Rong, J. and Zhang, J.Y. (1998). Application of Break-down Theory in Traffic Flow Modeling. Proceedings of International Symposium of Highway Capacity, Nanjing.