Characteristics of Chinese Driver Behavior

Jie Li

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Dedicated to my family

Preface

I will always remember the moment in 2006 when I received a call from dean Xiao: do you like to take the chance to study in the Netherlands? Without second thought, I replied ‘YES’! I did not yet know I had to get a qualified score of IELTS and an invitation from the Netherlands in three months. At that time, my English was so poor (even now, I still do not think my English is sufficiently good) and the Netherlands was just a beautiful country out of my world. After three months of hard study of English, I was lucky to pass IELTS. With help from many friends, Delft University of Technology opened the door and accepted me as a PhD student in 2007. At that moment, I knew that a new chapter of my life was open. Pleasure, novelty, together with difficulty and frustration were waiting for me.

To me, doing PhD research is really full of happiness and misery. The happiness comes from every step forward, even if the improvement is small compared with the achievements of other researchers working at Delft University of Technology. Research has a magic power to inspire my potentialities by exploring new and more interesting research topics. In my case, the comparative study of driving behavior offers me a contrasting perspective on the world: education, culture, life, etc. However, feelings of misery appeared more often in the past several years. As a mother of a daughter in high school and being a part time PhD student from China, to be frankly speaking, I never dared to imagine the moment I get the doctor degree from Delft University of Technology. Doubting my ability in research almost became a habit. I was always under great pressure due to the slow progress. How could I fight with this pressure? Without the helping hands from my colleagues and friends, I could never overcome those difficulties. I would like to take this opportunity to thank these kind people.

Firstly, my thanks go to Henk van Zuijlen and Serge Hoogendoorn. Both of you support my research in effective ways. Henk supervises my PhD research, stimulates my interest for research, as well as inspires my confidence. I also appreciate Henk’s family for the delicate food made by Adrie, the cute bungalow offered by Hans, and the wonderful parties organized by Ellen. You give me the chance to know such a warm and loving Dutch family. I am also grateful for Serge’s support: specific comments, good ideas and the opportunity to work in such a good research group. Your achievements in research, just like your height, are impossible for me to reach. It is my great pleasure to get your professional contributions to my work.

Besides the support from my two supervisors, I enjoy very much the great research

environment created by the Transport and Planning department at the TU Delft and TRAIL. Doing research with so many kind and smart colleagues has been very inspiring for me over the past years. Special thanks are given to Elisabeth for the data collection and summary translation. Xiaomin, thanks for the propositions translation and the nice dinner with your family. I will always appreciate the help from Yusen, Qing, Huizhao, Hao, Nicole, Fangfang, Francesco, Meng, Yufei, Conchita, and many other people.

My PhD research has been made possible by finance from NUFFIC, DVS, Hunan University, Changsha Science and Technology Commission under number K1001010-11. I also kindly acknowledge the support of vZC, INRO, Grontmij and PTV. Your support gave me the chance to use the advanced transportation simulation programs for my research, and to link the research on theory with the work in practice.

I would like to appreciate Na's efforts in editing and reviewing this dissertation. I am grateful to my badminton friends, Haiyang, Ran, Zhuoyu, Han, Hui, Xuan, and all others, who gave me the feeling of a big warm family for the 26 months I spent alone in Delft. Doing PhD research and writing a dissertation takes lots of time. The open-minded research strategy of Hunan University, where I have a full time job as a teacher, made the part time research possible for me. Finally, I am deeply indebted to my family for all their understanding, support and patience. I would like to give my special thanks to Helen for the design of the cover. Helen, my dear daughter, I am proud of you!

I am a lucky woman! Since I received so much help and support over the past seven years, it is impossible to give my thanks one by one in this preface. I will always feel grateful and return this kindness in the future.

Jie Li（李洁）

Changsha, March 2014

Contents

Chapter 1

Introduction

1.1 Research Background

Transport, an important element of social-economic development of a town, a region, and a country, is tightly related to welfare, environment, daily life, etc. Transport as a system can be classified into three layers: transport patterns of goods and persons, transport services implying conveyance tools, and transport networks based on the physical transport infrastructure (Schoemaker *et al*., 1999). In this three-layer model, the interactions between the levels are described with market concepts: transport market and traffic market, which connect and regulate the supply and demand for transport and traffic. People's wish to travel is related to the first layer (i.e., transport patterns) and can be considered as a kind of transport demand. The driving activity concerns the second layer, namely transport services, which is influenced by the vehicle, the network, and the driving environment (van Nes, 2002). If the supply in the transport system can't cope with the demand, the service will deteriorate and the subsequent results can be the increase of travel time and delays, traffic congestion, and negative impact on the environment, etc. At present, almost every country experiences more or less pressure and problems from transport.

Over the last two centuries, transport in most developed countries has become a multimodal system which integrates different transport modes, such as trains, bicycles, vehicles, airplanes (Filarski, 2004). With the progress in technology, transport will continue developing in the future. Compared with Western countries, most developing countries have a lag of almost one century in industrialization and started motorization in transport only after the Second World War. At present, they are in a crucial stage: transport demand and transport supply both have blown out in the past decade (Lu *et al*., 2008).

The transport disequilibrium, caused by the transport demand increasing faster than the transport supply, is prevailing in metropolitan areas. People are attracted to cities where they find more working opportunities and better facilities in education and recreation than in other regions. This makes the urban transport demand rather high. Cities are often economic, cultural centers, and need to communicate with each other through the inter-city transport. The traffic demand between cities can be realized by extending the present transport network or adding new transport modes. However, it is difficult in dense cities to extend the road infrastructure due to the limited available space. Without appropriate management of transport, those problems will impose negative influence on living quality in cities and the transport will become a bottleneck for social-economic development. The scarcity of transport supply cannot be always solved by introducing more transportation means or by extending the traffic infrastructure. Therefore, the optimization and management of traffic demand together with transport infrastructure utilization has attracted more and more attention from transport researchers and authorities.

As a typical developing country, China has similar traffic problems described above. With the rapid economic development and fast urbanization process, traffic demand keeps increasing over the past 30 years. Traffic congestion and traffic safety are becoming more and more serious in Chinese big cities. As the biggest developing country and the largest vehicle market in the world, the solution for the transport problems in China can become a significant reference for other developing counties.

1.2 Problem Statement

Road traffic is an important transport component both in urban areas and in rural regions. In general, road traffic conditions are the results of complex interactions among four primary elements: drivers, vehicles, roadways and traffic management. Roadways are constructed based on the limitations of vehicles and drivers on the limited available space; and traffic management focuses on optimizing road traffic to enhance traffic safety and capacity. In reality, the driver is also an important part of road traffic and driver behavior can influence traffic performance to a certain extent. For instance, in China, one particular phenomenon is that priority rules on the road are not so clear to most drivers, which is an important cause for traffic accidents in urban areas. Furthermore, the confusion about the priority rules also considerably reduces the capacity of intersections. The other important factor strongly related to traffic performance is the high frequency of offences against the traffic rules in China. Among the recorded offences, aberrant lane changes take place most frequently (Heilongjiang Traffic Police Website, 2011a). It is still unclear why these drivers developed such aberrant behavior, and how this kind of behavior can be changed to improve the prospects of the transport system.

Traffic simulation models are an important tool for engineers and researchers to study traffic problems and develop traffic measures before implementing them in practice. Nearly all these simulation models were developed in Western countries and default parameters related to driver characteristics were determined based on driver behavior as observed in those countries. In developing countries, the traffic infrastructure, driving culture and driving experience all distinctly differ from those in Western countries. Those discrepancies all can influence driver behavior. For example, lots of drivers in China have a quite short driving age and are inclined to keep a long distance with the preceding vehicles. If a simulation model is applied in practice without calibration for the special local driver behavior, invalid simulation results will be produced by this model. Furthermore, there is a risk that inappropriate traffic measures will be carried out in reality based on such unrealistic simulation results.

In literature, most research related to the improvement of microscopic simulation models was based on the local regular driver behavior. The interaction between traffic performance and driver behavior, national driver behavior characteristics and the implication for the modification of simulation models attracted scarce attention from researchers. Furthermore, the international comparative studies on traffic characteristics in urban areas are rarely addressed in literature. How much does the driver behavior contribute to the discrepancies in national traffic characteristics? This question cannot find an answer in available publications.

From the research view, driver behavior, traffic characteristics, and traffic simulation models are three quite large and general topics. It is impossible to elaborate all three research topics in one dissertation. The main research questions and the corresponding sub-questions addressed in this dissertation are listed as follows:

1. What are the differences in traffic characteristics between different countries?
   - What factors can contribute to these differences ?
   - What are the effective ways to improve traffic performance?
   - What is the role of driver behavior to traffic performance?

2. What are the differences in driver behavior between different countries?
   - What factors can influence driver behavior?
   - Does national culture play an important role in driver behavior development?
   - What kind of survey methods can be used to investigate these differences?
   - How can the results of a driver behavior survey be verified?
   - What are the appropriate ways to improve driver behavior?

3. How to calibrate a microscopic simulation model based on the investigation of driver behavior?
   - How can the results of a driver behavior survey be used to calibrate simulation models?
   - What are the implications for model improvement?

In order to answer these questions, comprehensive surveys of traffic performance and driver behavior have been carried out in this study. The survey results and theoretical analysis are presented in this dissertation to reveal the relationship among traffic performance, driver behavior and simulation models.

1.3 Research Scope and Objectives

The transport system is complicated since it involves many components: traffic modes, infrastructures, participants, traffic and transport management, and so on. The importance of transport to people's daily life attracts large numbers of researchers to study and improve it from different aspects. A researcher has to limit the research scope based on his/her domain of knowledge, study experiences, research possibilities and available time.

Research Scope

First of all, the comparative study of traffic performance and driver behavior needs to determine the survey countries and data-collecting locations. China and the Netherlands, as two countries that have typical characteristics of a developing and a developed country respectively, are selected to conduct traffic surveys in this dissertation. On account of the fact that traffic congestion and the corresponding negative impact on the environment are both more seriously present in big cities than in other regions in China (Lu *et al*., 2008), the data collection will be restricted to road traffic in urban areas.

The travel time on urban cities is determined by traffic volumes, traffic control, saturation flow rates, and desired speeds (Zheng, 2011). Traffic control and saturation flow rates are both strongly related to signalized intersections. In lots of cities, the poor performance of signalized intersections is one important cause of congestion. Therefore, the research in this dissertation focuses on the traffic performance and driver behavior in regions with signalized intersection.

Saturation flow characteristics, especially saturation flow rates, are most associated with the traffic performance at signalized intersections. Some previous studies demonstrated that the saturation flow rates in developing countries' cities were much lower than the values measured in Western countries (Hossain, 2001; Vukanovic *et al*., 1994). From the investigation done in Beijing and Shanghai in China, van Zuylen *et al*. (2003) found that the traffic composition in these Chinese cities was not so different from that in Western countries, but saturation flow rates of the through going lanes were reduced by 35% compared with the values measured in the Netherlands due to the inappropriate traffic control and the irregular behavior of drivers, cyclists and pedestrians. In order to identify the factors which can result in the differences in saturation flow characteristics, an investigation on saturation flow and the comparison between China and the Netherlands will be presented in this dissertation.

A few previous international comparative studies on saturation flow indicate that the external factors (e.g. road configuration, weather, signal control design, traffic composition) and driver behavior (e.g. reaction to signal, car following, lane changing) are two main aspects closely related to saturation flow characteristics. In the case that most external conditions (except signal control) are similar at the investigated intersections in this dissertation, driver behavior becomes the dominative factor for the traffic performance. Therefore, the driver behavior survey and comparison between China and The Netherland will be a part of the important content of this dissertation. Driver behavior can be surveyed in many ways. According to the study objectives and research possibility, questionnaire, focus group session and in-car test are applied in this study. The complexity of driver behavior is mainly determined by two classes of elements: driver personal properties (e.g. age, gender, driving experience) and impersonal properties (e.g. traffic conditions, weather, vehicle attributes). The factors influencing driver behavior and the driving style categorizing method will also be explored in this dissertation.

In practice, traffic performance is often analyzed by a simulation model. Model calibration and validation based on driver behavior is another important topic of this study. Macroscopic models mainly focus on the propagation of travel flow on the whole network based on some assumed behavioral model (Daganzo, 1997). Microscopic models can simulate vehicles' movement at the individual level. One advantage of microscopic models is the ability to characterize the interactions among vehicles and the reaction to external traffic conditions. Therefore, the simulation model studied in this dissertation will be on the microscopic level.

In summary, the research scope of this dissertation will be limited to Chinese driver behavior in urban areas, the comparison with Dutch drivers, the influence of driver behavior on traffic performance at signalized intersections, and the calibration of a microscopic simulation model. Lots of elements are relevant to the study subject 'driver behavior'. The logical relationship among these elements is shown in Figure 1.1.

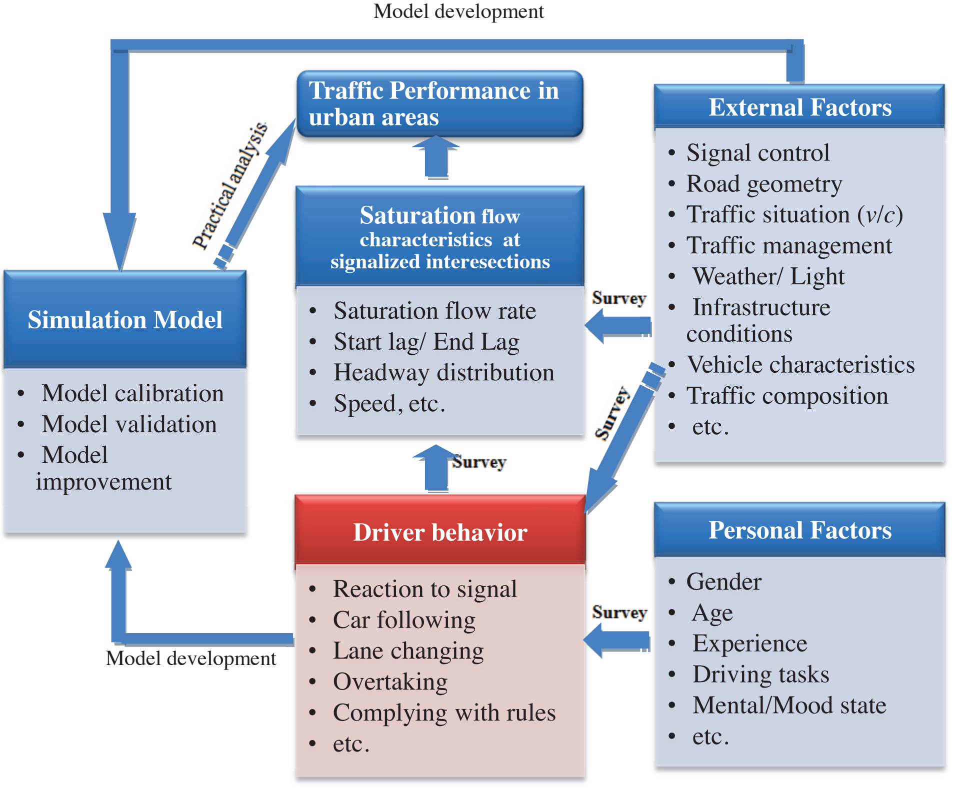


Figure 1.1 Logical relationship between driver behavior, traffic performance and simulation models studied in this dissertation

Research Objectives

Based on the research questions and research scope described above, the main objectives of this dissertation are to reveal the characteristics of Chinese driver behavior in comparison with Dutch driver behavior, to identify the influence of driver behavior on traffic performance, and to explore a feasible way to calibrate microscopic models with the survey results. These research objectives can be specified as follows:

- To identify the differences in the characteristics of saturation flow at signalized intersections between Chinese cities and Dutch cities, to reveal the factors which can significantly influence saturation flow rates, and to discover effective measures to improve traffic capacity and safety.

- To explore the differences in driver behavior between these two countries, to reveal the factors that can influence the driver behavior, to ascertain the traffic policy and social factors contributing to the development of driver behavior.
- To develop and validate a new method for microscopic simulation models calibration based on the categorized local driver behavior, to find out the feasible means to improve the present models.

1.4 Main Contributions

The contributions of this study can be distinguished in two parts: scientific contributions and practical relevance.

1.4.1 Scientific contributions

The research presented in this dissertation is a kind of foundational work for the study of driver behavior. Although many studies have been done with regard to driver behavior, it is important for developing countries, not only for China, to have an insight into the interrelationship among driver behavior, traffic performance and external traffic factors. The main scientific contributions can be classified into two parts: theoretical contributions and methodological contributions, which are summarized as follows:

1. Theoretical contributions

  - Getting new insight into driver behavior,
  - Revealing the relation between personal factors and driving behavior,
  - Modeling the interactions between traffic performance and driver behavior,
  - Modeling the influence of traffic conditions on driver behavior, and
  - Classifying driver behavior based on the data obtained in driver behavior surveys

2. Methodological contributions

  - Improvement of the regression method to calculate saturation flow rates,
  - Development of a product limit method for estimating saturation flow rates,
  - Development of a novel method to categorize driver behavior by factor and cluster analysis, and
  - Development of a new method for the microscopic simulation model calibration.

1.4.2 Practical relevance

The research results attained from this study have important implications for practice. The main practical contributions are listed as follows:

- Disclosure of reasons for the poor traffic performance in a Chinese city,
- Manifestation of an effective way to improve driver behavior and traffic performance,
- A simple and feasible method to extract desired acceleration and desired speed patterns from GPS data,
- A relative simple methodology for a microscopic simulation program calibration,

- Recommendations for traffic control design, traffic rule enforcement, and traffic management,
- Implications for transportation development and management policy.

1.5 Dissertation Outline

This dissertation is organized with three parts, as described as follows:
Part I: Research background,
Part II: Investigations and comparison,
Part III: Research application, conclusions and future research.

More details about these three parts are described in the following section.

Part I: Research background

This part of the dissertation starts with Chapter 2 which mainly introduces the road traffic development status in China. As a contrast country, Dutch traffic development status will also be introduced shortly. Some properties associated with developing countries and developed countries will be highlighted. Chapter 3 presents a literature review on studies about factors influencing driver behavior, international driver behavior comparison, and the relationship between driver behavior and traffic performance. These two chapters constitute the background of this research.

Part II: Driver behavior investigations and international comparison

This part of the dissertation consists of four chapters. Chapter 4 investigates the differences in saturation flow characteristics between China and the Netherlands. The reasons for the poor traffic performance in Chinese cities are revealed through a comparative study of the saturation flow characteristics at intersections in three Chinese and two Dutch cities. Chinese drivers adapt themselves to the local conditions and behave differently from Dutch drivers. This inspires the further surveys of driver behavior in this dissertation. A driver behavior questionnaire survey carried out in China and the Netherlands will be introduced in Chapter 5. After that, the differences in driver behavior in these two countries will be analyzed. The main factors influencing driver behavior will also be discussed. In order to verify the answers in the questionnaire survey conducted in China, in-car tests were made for thirty drivers in Changsha (China), as described in Chapter 6. Abundant information and data related to driver behavior were collected through three cameras and one GPS receiver. These empirical data will be used in the model calibration and validation. Even though the questionnaire survey and in-car tests have provided plenty of information relevant to driver behavior in China, drivers' thinking process in making driving decisions is still not clear and will be investigated through focus group discussion, as described in Chapter 7. The most interesting findings and conclusions from these focus group discussions will be presented.

Part III: Research application, conclusions and future research

Part II reveals the significant difference in driver behavior between China and Western countries. Therefore, most microscopic simulation programs should be adapted, calibrated and validated for Chinese situations. The calibration of present driver behavior model is the main topic of Chapter 8. A new and feasible calibration method and some suggestions about the simulation model improvement based on the driver behavior survey results are introduced in Chapter 8. Several main conclusions, recommendations for traffic management, and proposals for further research are presented in Chapter 9.

The appendices contain four parts. Appendix A introduces the important concepts relevant to driver behavior at signalized intersections. Appendix B discusses several methods for the estimation of saturation flow rates. The English version of Driver Behavior Questionnaire is presented in Appendix C. Finally, the questions discussed in Driver Behavior Focus Groups are listed in Appendix D.

The schematic overview of the dissertation outline is shown in Figure 1.2.

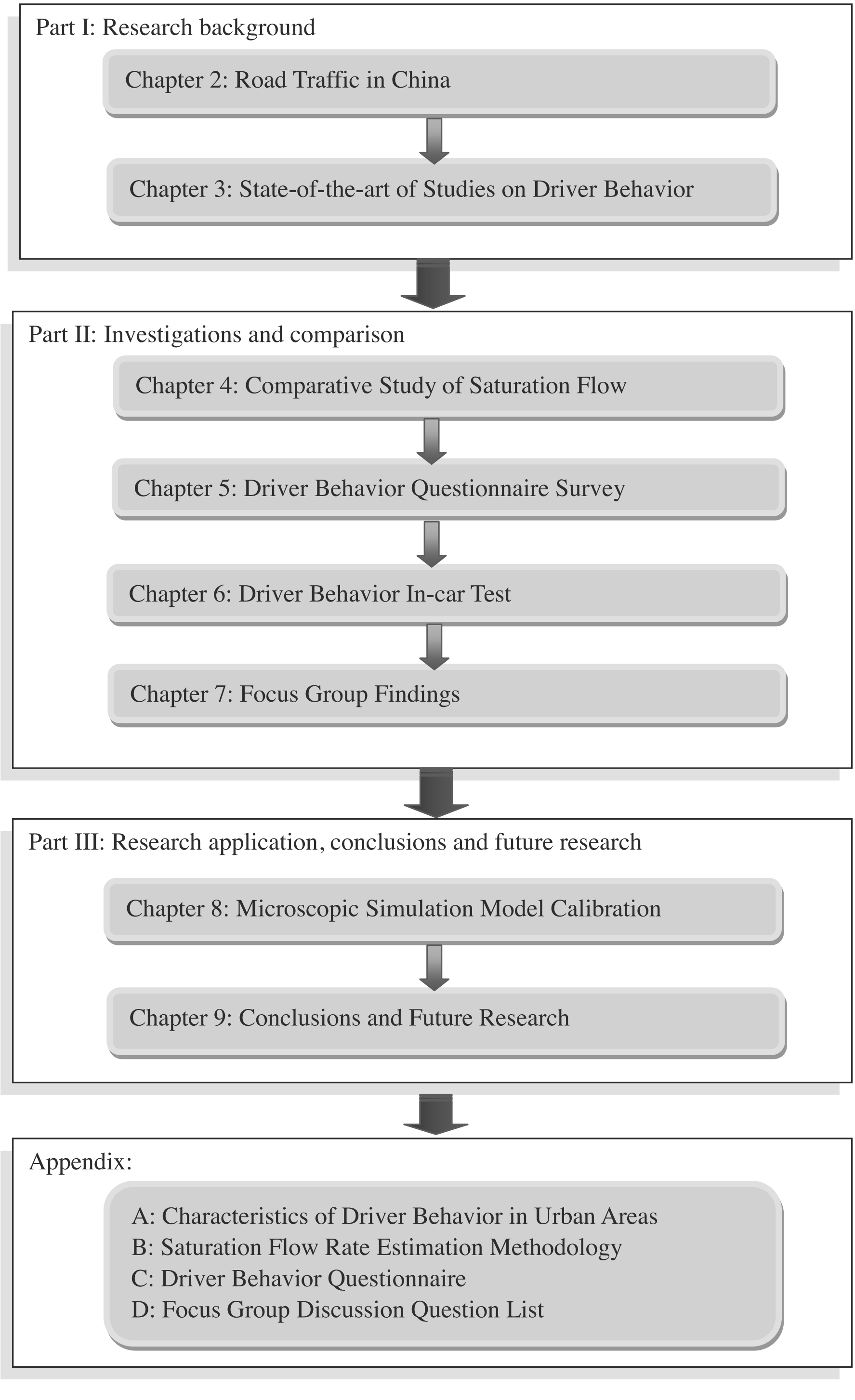


Figure 1.2 Schematic overview of the dissertation outline

Chapter 2

Road Traffic in China[1]

2.1 Introduction

One of the main research objectives in this dissertation is to reveal the correlation between Chinese driver behavior and traffic performance (as introduced in Chapter 1). Drivers are an important component of the road transportation system which is strongly related to the national economic development and urbanization rate. An insight into driver behavior cannot be obtained without the knowledge of transport development and present socio-economic conditions. Therefore, it is necessary to have an overview of the road traffic development status in China.

The rapid development of modern transport in China started from 1979 with the introduction of reform and opening-up policies. The socio-economic development in China increases the traffic demand dramatically and stimulates the fast progress of the transport system. Meanwhile China is experiencing a speed-up urbanization process. As an important indication of urbanization level, 'urbanization rate' is defined as the percentage of urban population in a country. In the period of 1978 – 2000, the urbanization rate in China increased from 17.92% to 36.22% and then reached 51.3% in 2010 (Zhang and Jing, 2012). In China, a 'city' is defined as a place with the resident population 'more than 100,000' (City Planning Law of the people's Republic of China, 1989). In term of this definition, the number of cities in China increased from 136 to 657 in the period of 1978 - 2010 (Ministry of Civil Affairs of the P.R.China, 2011). Urbanization in China is characterized by a high population concentration: one third of total population lives in 0.37% of the total land area (Lu *et al*., 2008).

The speed-up urbanization process influences the existing urban traffic patterns to a considerable extent. The expansion of urban space requires fast travel speed, which prompts the growing use of vehicles. For instance in Beijing, the proportion of bicycle travel declined from 60% to 40% between 1990 and 2000, while the proportion of the trips by private cars increased from 10% to 30% (Lu *et al*., 2008). This travel mode shift trend and the increasing traffic demand result in high pressure on the transport system in China, especially in the metropolis. In 2010, 29 cities had a population of more than 3 million. At present, all these

[1] This chapter is based on the paper: Road Traffic in China (2014), by Li J. and H.J.van Zuylen, *Procedia - Social and Behavioral Sciences*, 111: 107-116.

cities are facing some problems related to traffic, such as serious congestion, air pollution, and traffic accidents. The questions with respect to this background are: how do drivers develop their driving behavior? What is the interaction between driver behavior and the whole traffic surroundings? These questions should be addressed properly because they are relevant to the traffic safety and transportation efficiency. An overview of the road traffic development status in China is expected to answer following basic research questions:

- What is the vehicle ownership development level, and what is the development trend?
- What is the driving license and driver age distribution?
- What is the public transport development level in urban areas?
- How about traffic rule offences and what is the relation to traffic accidents?
- How about the road traffic safety and what is the relation to traffic congestion in urban areas?

This chapter firstly presents the development of vehicle ownership in China. A comparison of driver distribution is made between China and the Netherlands in section 2.3. After that, section 2.4 briefly introduces the development status of public transport in China. The traffic offences, traffic safety and the corresponding influence on traffic performance are described in section 2.5 and section 2.6 respectively. The relevance of these phenomena to the rest of this study is discussed in section 2.7.

2.2 The Development of Vehicle Ownership

Since 1979, the first year of the reform and opening-up strategy, the ownership of motor vehicles has been experiencing a constant growth. The civilian vehicle ownership annually increased about 21% in the period of 1978-2007 (Lu *et al*., 2008). From 2009, China has become the largest vehicle market in the world. The sale volume of vehicles in 2012 was 19 million (China Association of Automobile Manufacturers, 2013), the vehicle ownership in China exceeded 12.089 million and became the second largest vehicle country in the world (National Bureau of Statistic of China, 2013).

Passenger cars constitute the main part of vehicles in cities. The Gross National Income (GNI) per capita and Gross Domestic Product (GDP) per capita, as indicators of economic development in a country, are the main determinants for private passenger vehicle ownership (Chen and Zhang, 2012). From 2004 to 2012, the annual growth rates of GNI and GDP per capita in China were about 12.6% and 10.5 % respectively (The World Bank, 2013b). In this period, China experienced a rapid motorization process with an annual increasing rate of 24.1% in passenger cars per 1000 people, as illustrated in Figure 2.1.

Figure 2.1 Passenger cars per 1000 people in China (The world Bank, 2013a)
Note: Passenger cars refer to road motor vehicles, other than two-wheelers, intended for the carriage of passengers and designed to seat no more than nine people (including the driver)

The reference country in this study is the Netherlands which is a typical high income developed country. According to the statistics of The World Bank, the annual growth rates of GNI and GDP per capita in the Netherlands were about 3.6% and 1.2 % respectively in the period of 2004 - 2012. The vehicle ownership in the Netherlands keeps on a quite high level since 1970s' and still increases slightly every year, as shown in Figure 2.2. The number of passenger cars per 1000 people increased with an annual rate of 1.4% from 2004 to 2010. The ownership of passenger cars is in a quite stable status.

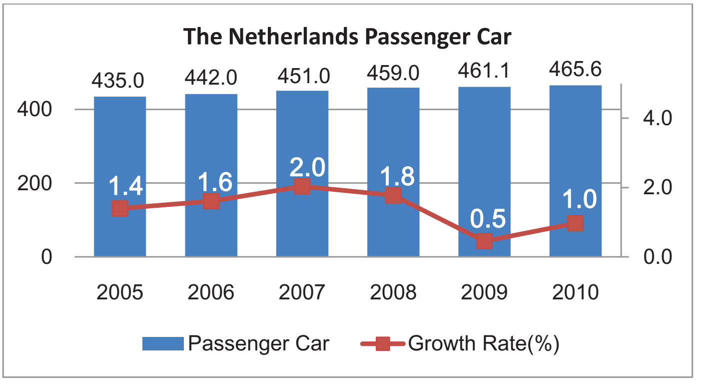


Figure 2.2 Passenger cars per 1000 people in the Netherlands (The world Bank, 2013a)
Note: Passenger cars refer to road motor vehicles, other than two-wheelers, intended for the carriage of passengers and designed to seat no more than nine people (including the driver)

It has been shown in other countries that the ownership of passenger cars tends to bloom when the GPD per capita achieves the level of 3000 US$ (Qi and Zeng, 2003). According to the statistics of the World Bank, Chinese GDP per capita was already 3,749 US$ in 2009 (The World Bank, 2013b). However, in 2009 the passenger car ownership was 34.5 cars per 1,000 people, and was still at a low level compared with the average of 124.3 over the world and 461.1 in the Netherlands. More details are shown in Figure 2.3. It means that in the next several years China will still experience a relatively higher growth of passenger cars and has to suffer an increasing traffic pressure.

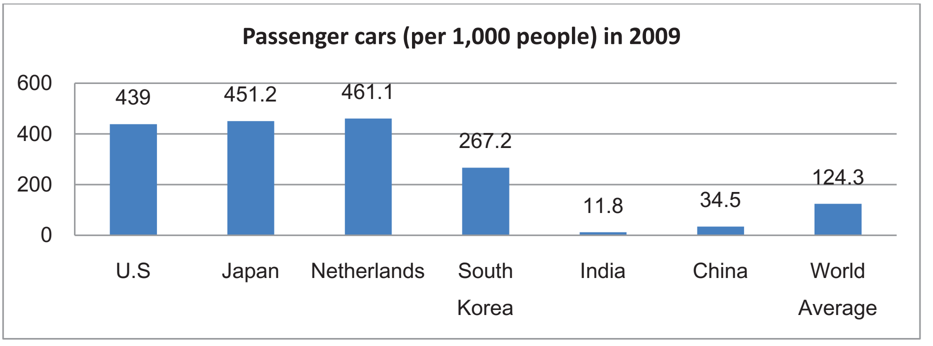


Figure 2.3 World-wide passenger cars per 1000 people in 2009 (The world Bank, 2013a)

At the same time, the ratio of the number of driver licenses to the vehicle ownership is also higher in China (1.66 in 2012) compared with the Netherlands (1.45 in 2003), which also indicates that private passenger vehicle ownership will still continue to increase in the future.

In China, just like in many other developing countries, the vehicle ownership and use of vehicles concentrate in urban areas. In 2011, 36 big cities possessed 34.54 % of the vehicles; 14 of these cities had more than 1 million vehicles; Beijing owned even 4.7 million vehicles (Traffic Management Bureau of the Ministry of Public Security, 2012a). At present, some Chinese metropolises (e.g. Beijing, Shanghai, and Chengdu) experience severe congestion during the peak hours.

2.3 Driver Distribution

Associated with the growth of vehicle ownership, the number of licensed drivers is also increasing quickly in China, which influences the composition of drivers. In the literature, the terms ‘young’, ‘new’, ‘newly qualified’ and ‘novice’ drivers are prevalent and are used interchangeably. The term ‘novice’ will be used in this dissertation and, unless stated otherwise, indicates a driver with a driving license shorter than 3 years. The annual growth rate of novice drivers is about 10% in China, as shown in Figure 2.4 (left). The number of drivers with less than 3 years driving experience is about 1/3 of the total driver population. Compared with China, the Netherlands has a quite low proportion of novice drivers, as show in Figure 2.4 (right). The drivers with less than 3 years experience only occupied less than 5% of the total driver population, based on the historical data from 1997 to 2004.

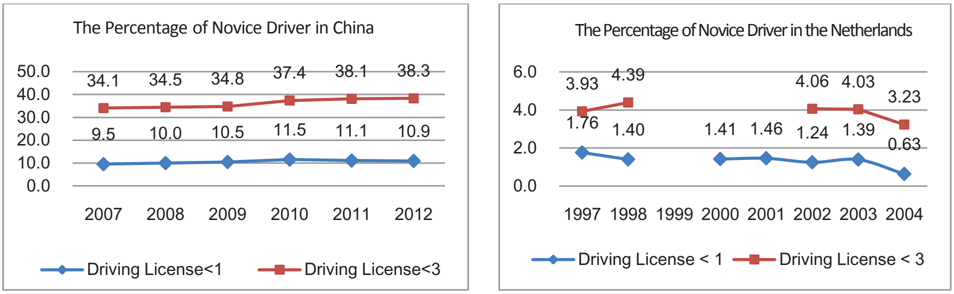


Figure 2.4 Percentage of novice driver in China (left) and the Netherlands (right)
Note: Data from Traffic Management Bureau of the Ministry of Public Security (2012a)

In the Netherlands, the drivers with less than 1 year driving experience only contribute a quite small part of the driver population (0.63% in 2004). Drivers with less than 3 years and 5 years of licensure only possess 3.23% and 5.97% respectively (see Figure 2.5). According to the research made by de Craen (2010), the lack of experience can lead to a high mental workload to the novice drivers. Any improper evaluation of the traffic situation and driver's operation errors can become an inducement to traffic accidents.

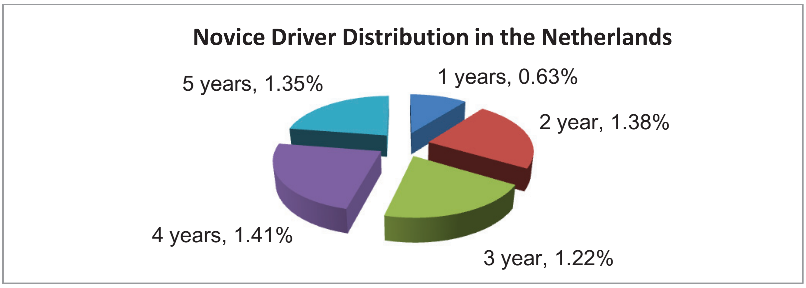


Figure 2.5 Novice Driver distribution in the Netherlands (2004)
Note: Date from Statistics Netherlands (2012)

In terms of the statistics made in 2011 in China, most drivers are between 26 and 50 years old, accounting for 79.04% of the driver population. Drivers younger than 26 or older than 50 both contribute about 10%. Almost half part of the Chinese drivers is at the age of 36-50, as shown in Figure 2.6. The proportions of very young drivers and very old drivers to the whole driver population in China are both low.

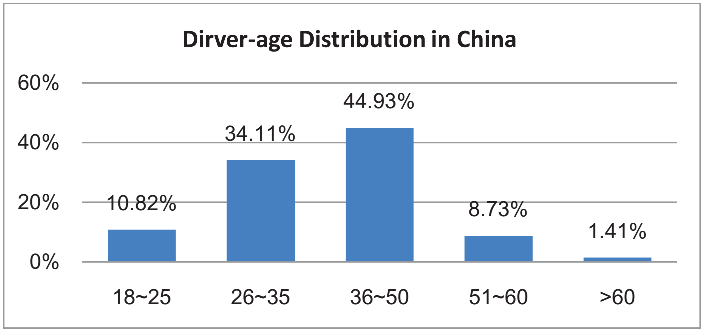


Figure 2.6 Driver-age distribution in China (2011)
Note: Date from Heilongjiang Traffic Police Website (2011b)

Lots of evidence proves that young drivers with limited driving experience behave differently from mature drivers, which has influence on both the traffic performance and safety (Houtenbos, 2008). The study made by de Craen (2010) shows that driving experience is more significant to crash risk than drivers' age, even though it is difficult to separate these two factors. In China, novices are a quite large part of the driver population and their driver behavior is expected to be improved with the accumulation of their driving experience. This leads to the research question whether Chinese drivers' behavior can be mainly ascribed to their inexperience. Chapter 5~7 will give a further study on this question.

2.4 The Development of Public Transport

Compared with the sharp increase of private vehicles, the development of public transport in the past decades was slow in aspects like: the number of buses in operation, route line mileage, and passenger volume, the level of service, etc. (Lu *et al*., 2008). Since at present congestion is a typical urban problem in China, the role of public transport is obviously significant (Mogridge, 1997). If more road infrastructure is constructed to facilitate motorized traffics, the accessibility of cities will be deteriorated unless public transport is also improved. The improvement of public transport is also beneficial for the car traffic because congestion will be reduced by the modal shift from private cars to public transport.

At present, Chinese national policy is to give priority to the development of public transport. The metro systems are rapidly extending in many large cities at a quick pace that is unique in the world. In 2013, 36 cities got approval to build a metro system with the total mileage of 6,000km (Li, 2013). At this moment, the total metro mileage in operation in 17 cities already reaches 2,100km. According to the national urban rail system plan, the number of cities with a metro system will be at least 50 in 2020. The metro system of Shanghai and Beijing both have been extended to more than 400km in the past decade. Even though this rail infrastructure is considerable, the metro rail per inhabitant is still quite low. In Beijing, every million inhabitants only have 20 km metro rail which is only about one third of the metro rail per million inhabitants in Amsterdam.

Bus Rapid Transit (BRT), as a kind of special bus systems, receives priority at intersections and uses dedicated infrastructure. The first line of BRT was developed in 2005 in Beijing.

Afterwards, 8 other Chinese cities started the experiment of BRT. However, the number of BRT lines, mileage and the passenger volumes conveyed by BRT are still quite limited (Kunming Urban Transport Institue, 2011; Wang *et al*., 2012) .

In 2004, the Chinese government set the development targets for Public Transport (PT): 30% travel service share in the mega cities and 20% in the big and medium sized cities (Wang *et al*., 2012). After several years' construction and development, the PT mode share is indeed increasing in some cities: e.g. from 24.1% in 2005 to 30.3% in 2010 in Beijing, from 14.7% in 2005 to 23.7% in 2009 in Kunming, etc. Some other factors can also influence the travel mode choice. For example, the conduct of the 2008 Olympics Games in Beijing had accelerated the development of PT. The experiments of BRT in Kunming might have stimulated PT ridership. However, Shanghai has just the opposite trend: PT share decreased from 26.0% in 2005 to 23.2% in 2009.

The survey conducted by King *et al*. (2014) shows that only one third of car owners in China always drive their car for commuting and leisure. This survey was carried out in the whole country, thus the data from urban areas and rural areas were mixed. The investigation results still indicate the good opportunities to increase the PT mode share notwithstanding the widespread adoption of cars. In short, public transport in China has great development potential. Since this dissertation focuses mainly on private road traffic, the interesting and important subject of public transport in Chinese cities will not be elaborated further.

2.5 Traffic Rule Offences

Compared with the traffic in China, traffic flows in most Western countries are rather smooth due to the fact that the majority of drivers behave in a consistent and predictable way (Li *et al*., 2012). Homogeneity makes flows more efficient and turbulence caused by aberrant behavior of individual drivers often reduces average speeds and traffic throughput. Therefore, obedience to the traffic rules and driving in a disciplined way can help drivers to know and to predict each other's movement. In this case, drivers can drive more confidently with less reason to 'expect the unexpected' (Houtenbos, 2008). This section gives some insights into the offences made by Chinese drivers. More information regarding this issue can be found in Chapter 7.

In the first half year of 2011, Chinese traffic policemen totally recorded about 171 million cases of offences against the traffic rules: 26.3% of cases were slight offences and were warned orally before release, 73.3% of cases were penalized by giving the drivers a summons. Among the penalized offences, 54.7% took place in urban areas, and 34.9% and 10.4% were made on highways and freeways respectively. The distribution of penalized offences in different regions is shown in Figure 2.7 (left). Totally there were 25.6 million drivers recorded with offences, namely 11.4% of the total driver population had registered offences in half a year. The statistics data show that drivers at the age between 30 and 50 years contributed 69% of the offences. Given the fact that this group is about 63% of the total population, this high percentage of offences is understandable. More details can be seen in Figure 2.7 (right). It can be preliminarily concluded that the age is not significantly relevant to the record of offences in China.

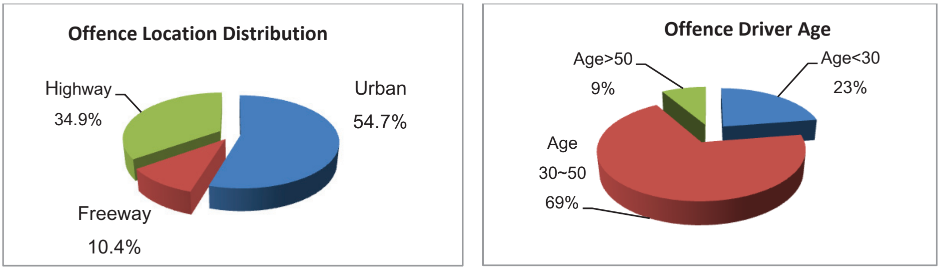


Figure 2.7 Offences on different roads (left) and made by different driver age groups (right)
Note: Data from Heilongjiang Traffic Police Website (2011b)

Further statistical analyses have been done for the offence data from October, 2011. October is a typical working month in China without festivals after 1st October (National Day). Compared with other road users, drivers made the largest proportion of offences with a percentage of 85.9. The percentages of offences made by cyclists and pedestrians/passengers are 7.5 and 6.6 respectively, as shown in Figure 2.8 (left). It is not sure whether these official statistics can demonstrate the offences of all road users, since traffic police men might pay more attention to drivers than to pedestrians and cyclists.

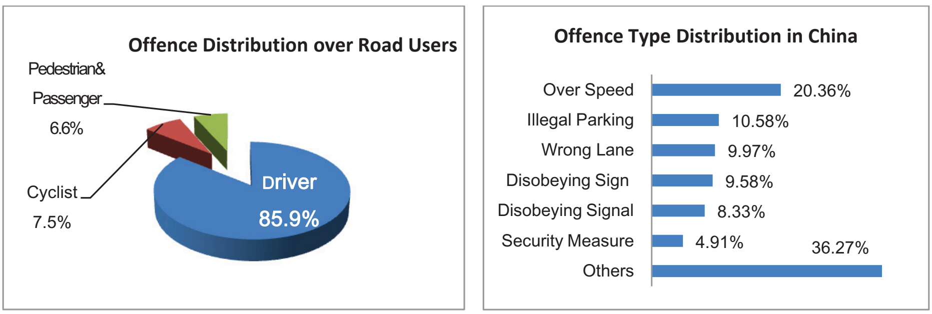
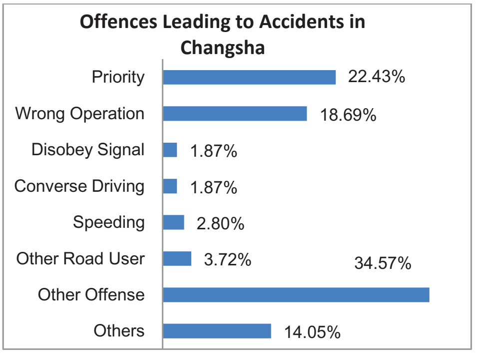


Figure 2.8 Offence distribution over road users (left) and offence types (right)
Note: Data from Heilongjiang Traffic Police Website (2011b)

Speeding was the most frequent offence and contributed 20.36% of the penalized offences in China in October, 2011. Driving at an excessive speed was a typical offence on freeways and motorways, where 70.6% of such aggressive behavior was recorded. The other frequently penalized offences were illegal parking, driving on wrong lanes, ignoring signs and signals. These are all typical offences in urban areas. Besides the above described offences, over-loading, driving while intoxicated, fault in vehicle light using, etc., were named as ‘Others’ in the statistics, which constituted 36.27% of penalized driver behavior. More details are shown in Figure 2.8 (right)

Traffic rule offences are an important inducement to traffic accidents in China. In 2004, the percentage of traffic accidents induced by drivers’ failures is 89.8, which constituted 87.4% of deaths and 90.6% of wounded in traffic accidents (Su, 2005). The most dangerous offences in China are speeding and ignoring priority rules which constituted 14% and 11.9% of the traffic fatalities respectively in 2010. The survey presented in Chapter 5 and Chapter 6 both identify that speeding and ignoring priority rule are quite often observed in China. The potential reasons are revealed in Chapter 7.

In urban areas, the main inducements to traffic accidents are usually different from those in the countryside. In Changsha, the capital of Hunan province, ignoring priority rules is the most dangerous behavior, since this kind of offences led to 22.43% of traffic accidents in June, 2012. Ignoring signals, illegal u-turns, and speeding together resulted in 10.3% of traffic accidents. These kinds of offences are typical examples of improper driver behavior which are expected to be improved by education. The distribution of traffic accident causes in Changsha is shown in Figure 2.9 (left).



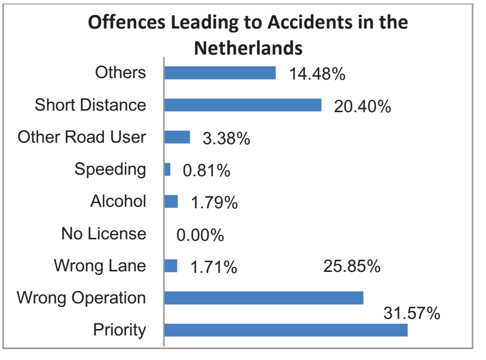


Figure 2.9 Accident cause analysis in Changsha (left) and the Netherlands (right)
Note: Data from Ren (2012) and Statistics Netherlands (2012)

The causes of traffic accidents in the Netherlands are shown in Figure 2.9 (right). The distribution over the offence categories is not significantly different between the Chinese and Dutch data, apart from the fact that driving on too short distance is an important cause of accidents in the Netherlands. This can be attributed to the behavior of Dutch drivers who dare to keep short time headways even at high speeds. This property of Dutch driver behavior is relevant to traffic safety, while it still results in a high traffic capacity. In China, every driver has to be cautious to avoid the possible danger created by other drivers. This is embodied in the slow acceleration and the large time headways (more details are in Chapter 7). This kind of caution in driving should not be criticized from the viewpoint of traffic safety; however its influence on traffic capacity is negative.

Drivers can be deterred from offending the traffic rules to a certain extent with the thought that their offences will be recorded and penalized. The registered and penalized offences can be considered as a kind of experience to a driver who may change his/her driving behavior afterwards. At the same time, many others also change their behavior, not because of the penalty experience, but due to the threat of penalties. However, when a traffic rule is offended without any penalties, the consequence will be that more and more drivers ignore this rule. This opinion is confirmed by the focus group interviews described in chapter 7.

2.6 Traffic Safety

Nowadays, traffic safety has become a global problem. Every year more than 1 million people are killed and up to 50 million are injured on the roads in the world(Bliss and Breen, 2009). *In developing countries, the under-developed traffic infrastructure used by inexperienced drivers with a faulty emergency rescue system leads to numerous accidents with a high rate of casualties*. Over 90% of the deaths on the roads occur in low-income and middle-income countries, which have only 48% of the registered vehicles in the world.

According to the prediction made by Turner *et al*. (2004), global road fatalities will increase by more than 65% from 2000 to 2020, unless intensified safety interventions are implemented. Fatalities are predicted to increase by more than 80% in low and middle-income countries, but decrease by nearly 30% in high-income countries (Filarski, 2004). Successful programs in high-income countries over the last thirty years have demonstrated that road deaths and injuries are preventable; therefore, road crash costs in low and middle income countries can be substantially avoided. *Sustainable Safety* project in the Netherlands is a leading example of good practice and the *Safe System* approach introduced by this project can be a significant reference to all countries (Bliss *et al*., 2011).

Traffic safety is a responsibility taken by governments and all road users. The relevant national activities have been carried out in many developing countries. The Chinese government made many efforts to increase traffic safety in the past ten years by improving the road infrastructure and strengthening the enforcement of traffic rules. The effect is visible in the decrease of the number of casualties due to traffic accidents, as shown in Table 2.1.

Table 2.1 The number of registered drivers, fatalities, death and injured in China

Year	Fatality	Death	Injured
2001	754 919	105 930	546 485
2002	773 137	109 381	562 074
2003	667 507	104 372	494 174
2004	567 753	99 217	451 810
2005	450 254	98 738	469 911
2006	378 781	89 455	431 139
2007	327 209	81 649	380 442
2008	265 204	73 484	304 919
2009	238 351	67 759	275 125
2010	219 521	65 225	254 075
2011	210 812	62 387	--

Note: Data from Traffic Management Bureau of the Ministry of Public Security (2012b)

Death ratios to 1000 vehicles in China in the period of 2007 -2011 are shown in Figure 2.10. In 2007, the fatality ratio was 1.4 deaths per 1000 vehicles, which decreased to 0.6 in 2011. A comparison of traffic incidents between different countries is not easy, because of the absence of identical international standard for the accident analysis. For example, the definition of 'died due to a traffic accident' is often different in different countries. A preliminary comparison between the Chinese and the Dutch statistics is shown in Figure 2.10. The death ratio in the Netherlands is much lower than that in China. The fact that more than 20,000 people died due to traffic incidents indicates that the traffic safety situation in China still has opportunities for improvement. Road safety in China will not achieve the level as in the Netherlands unless more and more people make joint efforts to improve the traffic safety.

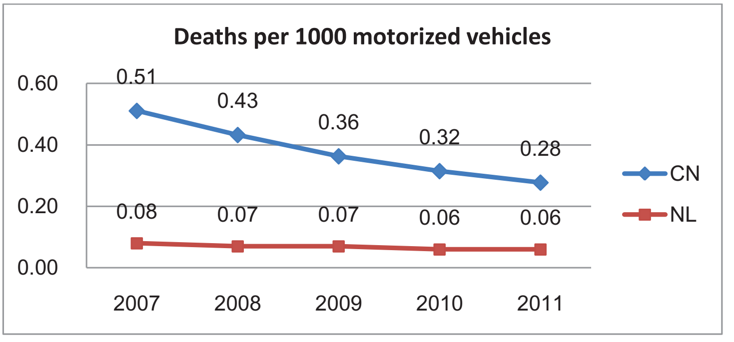


Figure 2.10 Deaths per 1000 vehicles (2007~2011)

Note: 1. Data from Traffic Management Bureau of the Ministry of Public Security (2012b) and (Statistics Netherlands, 2012); 2. Vehicles include cars, buses, and freight vehicles but do not include two-wheelers.

Traffic accidents are an inducement to traffic congestion, as well as a direct cause of traffic fatalities. For instance, in Changsha in June 2013, 24% of the congestion was caused by traffic accidents. Except for an imbalance between the traffic volume and the road capacity, traffic accidents were the main cause of congestion. Figure 2.11 shows the congestion reason analysis in Changsha city.

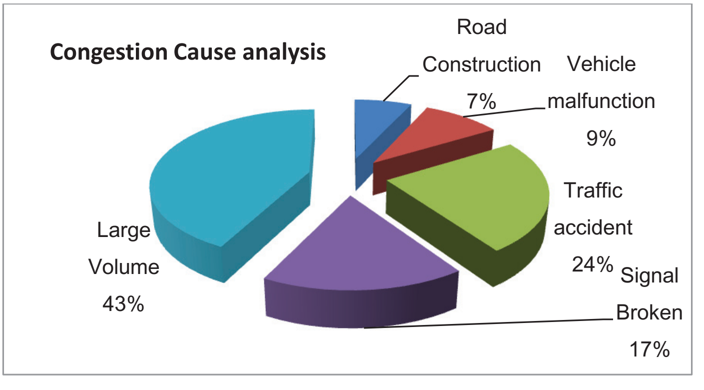


Figure 2.11 Congestion cause analysis in Changsha, June, 2013

Note: Data from Huang (2013)

In short, traffic safety is a global issue which should get attention from every participant of traffic. Driver behavior plays an important role in traffic accidents. The improvement of driver behavior is directly beneficial to traffic safety as well to traffic performance.

2.7 Conclusions

Nowadays, the changes of transport happening in developing countries are a kind of reproduction of the transport development that has taken place in Western Europe and North America after the Second World War. The difference exists in the development speed and scales: fast development speed on an enormous spatial scale in some developing countries, like in China. It should be highlighted that Chinese driver behavior is linked with the rapid urbanization process, the economic growth, and the quick development of the transportation infrastructure. Knowledge about the present transportation system development status should be the first step in addressing the traffic performance and driver behavior in China. Though an overview of the road traffic development status in China, some important conclusions are summarized as follows:

- *The vehicle ownership in China is still low, and the growth rate is large.*

China is the second largest vehicle country and the largest vehicle market in the world. However, in 2009 the passenger car ownership was 34.5 cars per 1,000 people, and was still at a low level compared with the average of 124.3 over the world. A large growth of passenger vehicle ownership is still expected in the near future.

- *The proportion of novice drivers is large.*

In China, the annual growth rate of novice drivers is about 10% and the number of drivers with less than 3 years driving experience is about 1/3 of the total driver population. Due to the constant increase of new cars and novice drivers, the effect of novice drivers with limited driving experience on the traffic performance will continue for many years. Drivers younger than 26 or older than 50 both contribute about 10%. Almost 50% of the Chinese drivers are at the age of 36-50. Therefore, the proportion of very young drivers and very old drivers to the whole driver population in China are both low.

- *Public transport develops slowly, but has huge potential.*

The development of public transport in Chinese cities in the past decades was slow compared with the rapid increase of the number of private vehicles. The still relatively low level of vehicle ownership provides opportunities to increase the PT mode share before widespread adoption of private passenger cars. At present, Chinese national policy has given more attention to the development of public transport, especially urban metro systems. The public transport mode share is increasing in some Chinese cities.

- *Traffic rule offences are common in China, and are a significant inducement to traffic accidents.*

In the first half year of 2011, 11.4% of the total driver population had been registered with offences they made. Speeding is a typical offence on freeways and motorways. Illegal parking, driving on wrong lanes, offending signs and signals are frequently found in urban areas. The most dangerous offence on freeways in China is speeding. In urban areas, the most important inducement to traffic accidents is ignoring priority rules.

- *The fatality ratio is still high in China. Traffic accidents are an important inducement to congestion in urban areas.*

Reducing traffic accidents is a shared responsibility for all road users, infrastructure designers and traffic managers. In China, many efforts have been made to increase traffic safety in the past ten years. Even the Chinese fatality ratio decreased by more than 50% from 2007 to 2011; the death ratio in China is still much larger than that in the Netherlands.

This chapter presents the evidence that Chinese socio-economic conditions, traffic development status, and driving license distribution are all different from those in North America and Western Europe. Chinese drivers develop their driving behavior in this special context. The influence of driver behavior on traffic performance is illustrated in Chapter 4. The answer to 'What is the typical Chinese driver behavior' and 'How people develop their driver behavior' can be found in Chapter 5~7.

Chapter 3

State-of-the-Art of Studies on Driver Behavior

3.1 Introduction

Traffic safety and efficiency have become important indexes for assessing the performance of transportation. Consequently, many efforts have been undertaken to improve transportation systems in the world with respect to these indexes. It is obvious that driver behavior plays an important role in traffic safety and efficiency. In the past decades, much research related to driver behavior has been done in the world. This chapter focuses on the available studies on characteristics of driver behavior.

Due to the complicated relations with a variety of factors, drive behavior has been intensively addressed in the literature. The complexity of driver behavior is mainly determined by three classes of elements:

1. Driver personal properties, including age, gender, driving experience, etc;
2. Vehicle characteristics, such as size, automotive power, control stability, etc;
3. Contextual conditions, comprising traffic conditions, weather, infrastructure conditions, etc.

Besides the above listed elements, national driving culture also has influence on driver behavior to a certain extent. Countries can differ in motorization stage, driving license examination system, traffic management, and traffic rules. Driver behavior is developed in a specific driving culture atmosphere and is characterized by national properties. The comparison of driver behavior among different countries has been done in some studies, even though limited, are discussed in this chapter.

The literature on driver behavior is huge and it is impossible to introduce all in one chapter of the state-of-the-art. According to the research objectives and the research scope of this dissertation (described in Chapter 1), this chapter focuses on the studies relevant to driver behavior. The literature related to characteristics of driver behavior can fall into three parts: factors impacting driver behavior, the influence of driver behavior on traffic performance, and the international comparative study of driver behavior. The main outline of this chapter is shown in Figure 3.1.

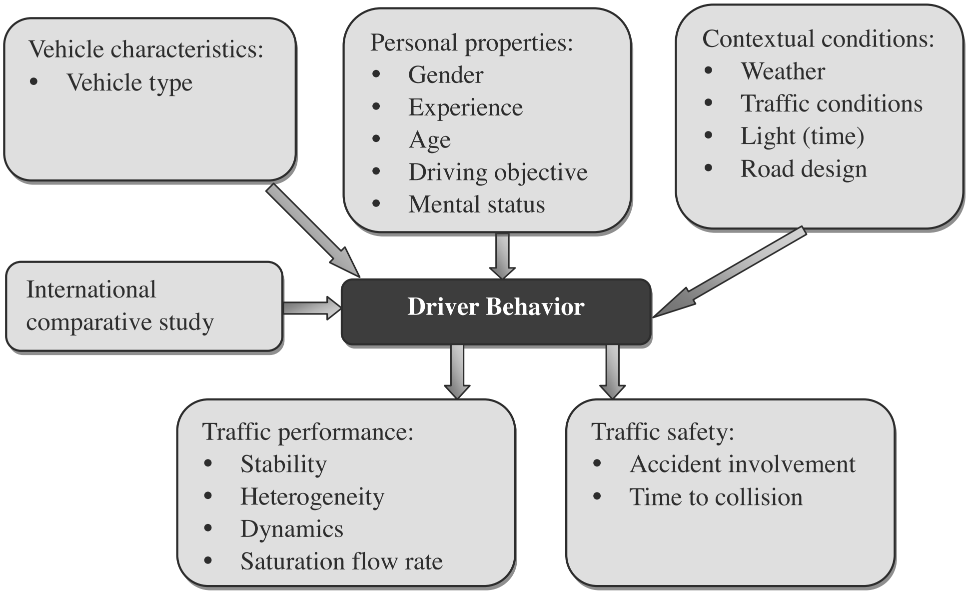


Figure 3.1 Schematic overview of the literature

In this chapter, the studies of factors which can influence driver behavior are introduced in section 3.2. Furthermore, an overview of the influence of driver behavior on traffic safety and performance will be presented in section 3.3. Thereafter, section 3.4 deals with an overview of international driver behavior comparison. Finally, section 3.5 summarizes the achievements and limitations of the previous studies. Through the state-of-the-art presented in this chapter, the existing knowledge relevant to characteristics of driver behavior is examined, the knowledge gaps are described, and the motivations for this study will be highlighted.

3.2 Factors Influencing Driver Behavior

The driving behavior is a comprehensive term that includes a variety of characteristics in driving. To a driver, the basic requirements in driving are safety, comfort, and timeliness. In order to satisfy these requirements, drivers firstly have to deal with different sources of information, thereafter to make a series of decisions, and then to execute a series of maneuvers. The complexity of the process of information collecting, decision making, and maneuvering contributes to the variety of driver behavior, as can be observed in reality.

Many studies have been carried out to reveal the factors that affect driver behavior significantly. As described in Section 3.1, driver behavior is mainly determined by driver personal properties, vehicle characteristics, and contextual conditions. Therefore, this literature concentrates on these three classes of elements. A review of these publications is expected to reveal what factors should attach more attention in this study.

3.2.1 Personal properties

From the above description, driving can be considered as a continuous process of perceiving information, making decisions, and executing maneuvers. It has been shown in many publications that several human characteristics can influence the driving process distinctly. One important conclusion made by Ossen (2008) is that heterogeneity, i.e. differences in driver behavior, caused by driver characteristics is larger than what currently is assumed in microscopic simulation tools. This section reviews the research on the influence of personal properties on driver behavior.

1. Gender

Many studies have been done to analyze the role of gender in driver behavior or driving safety. There are two different kinds of conclusions drawn from those researches made in different countries:

- *Male drivers are more aggressive and more frequently involved in risky driving*

Because male drivers are considered to drive more often than their female counterparts, de Craen (2010) firstly corrected the mileage, then found that young male drivers (age of 18-29 years) had a much higher probability to be involved in serious crashes than young female drivers in the Netherlands. In order to reveal the different types of crashes in which young drivers are involved, Monárrez-Espino *et al*. (2006) carried out a study and found that the male drivers' crash rate was five times higher than that of female drivers' in the early years of driving when the crash only involves a single vehicle. If more than one vehicle were involved in the crash, no significant difference existed between females and males. Forsyth *et al*. (1995) revealed two main factors which account for the difference in crash involvements between male and female drivers. The first factor is the type of trips: female drivers mainly drive with daily targets (e.g. working, shopping, etc); while males drive more often for leisure (e.g. young male drivers often drive with friends at night). The other reason is that males' driving style are often characterized as more risky than females', owing to speeding and driving after drinking. Whereas, Begg and Langley (2001) demonstrated that risky driver behavior decreases rather quickly with the increase of driving experience. Especially after the first year of driving, many novice male drivers become 'maturated' and change their risky driving style.

- *No substantial differences in the crash rates between male and female drivers*

Ryan *et al*. (1998) studied the risky driver behavior of young drivers between 17 and 24 years old in Western Australia. One important conclusion drawn from this study is that male and female drivers don't differ significantly in crash involvements when taking mileage into account, which is contrary to the research results got in the Netherlands (de Craen, 2010). After correcting the factor of mileage, Kweon and Kockelman (2003) drew a similar conclusion from the investigation of crash rates in U.S. The Driver Behavior Questionnaire (DBQ) survey conducted by Bener *et al*. (2008) showed that only very small difference existed between males and females in the DBQ item scores, indication of risky driving behavior, in Qatar and United Arab Emirates. Jelenova (2006) observed four intersections for 24 hours in Kosice, Slovakia, to examine the correlation between driver age and gender, traffic density and aggressive driver behavior. Gender differences in aggressive driver behavior were not found in this study. Mynttinen *et al*. (2009) investigated the self-assessed driving competence in Finland and Sweden and did not find a difference in the ability of self-assessment between males and females.

In conclusion, several studies have been done to analyze the difference in driver behavior between male and female drivers, but the research results are not consistent with each other. Most studies show that male drivers are more risky in driving than female drivers. The difference becomes faint when the drivers either become older or get more driving experience. This dissertation also investigates the difference in driver behavior between males and females in both China and the Netherlands. More details are shown in Chapter 5 and 6.

2. Experience and Age

Young drivers are often considered as novices with a lack of experience. A conclusion made by de Craen (2010) is that young novices are more risky in driving compared with old experienced drivers, especially considering the frequency of involvement in traffic crashes. The high crash risk of young novice drivers may be related to several factors: brain developing, intentional risk taking, lack of experience, etc.

- *Brain developing*

Paus *et al*. (1999) and Sowell *et al*. (1999) all stated that the human brain is still developing at the late stage of adolescence. In most countries, people are not licensed before the age of 18. After the age of 18, the driving related execution abilities, such as planning, impulse control, and the information processing, will still develop (de Craen, 2010). Thereby, the immature biological brain status can be regarded as a factor which can influence young drivers' behavior. In this dissertation, age is introduced to the factor analysis of driver behavior in Chapter 5.

- *Intentional risk taking*

Based on a 24-hour observation survey made in Kosice, Slovakia, Jelenova (2006) revealed that younger drivers appeared to have a greater tendency toward risks than older ones, owing to the living style and limited impulse control ability. According to the data collected among young drivers in Denmark, Moller and Gregersen (2008) developed a function of risk-taking driver behavior with some parameters to represent personal properties. This function indicates that some factors, such as leisure time activities and educational attainment etc., influence young drivers' driving behavior significantly. Harrison *et al*. (1999) found that high speed is an important inducement to young drivers' crashes in Australia. The percentage of crashes due to speeding made by young male drivers and young female drivers were both higher than that made by older drivers: 30% and 21% vs. 15%. Besides speeding, alcohol and drugs are also proved to have a significant influence on young drivers (Preusser and Leaf, 2003). In this dissertation, only the driver behavior during daytime in urban area is studied. Therefore some special life-style factors related to nighttime are not within the scope of this study.

- *Lack of driving experience*

According to the degree of conscious control, Rasmussen (1983) distinguished the human behavior into three levels: skill-, rule-, and knowledge-based (SRK) performance. On the knowledge based level, people carry out a task in an almost completely conscious manner, which takes considerable mental efforts. This is similar to a situation where a novice is performing the driving task or an experienced individual is exposed with a completely novel situation. The skill based level refers to the smooth and automatic execution of a task, often without conscious thinking. The conscious manner of the rule based level is between that of the knowledge and skill based levels. Knowledge based actions require much more time to decide and execute than the nearly instantaneous skill based actions.

Driving requires drivers to have the skills to possess a variety of information and to make corresponding decisions. After that, drivers need to carry out a series of maneuvers, e.g. steering, changing gears, operating the pedals, to achieve his/her driving tasks. Experienced drivers can take most actions automatically with less mental workload on account of their knowledge and practical experience. On the contrary, novice drivers have to perform the task with more attention, heavier mental workload. In complicated situations, some novices even use the rule of thumb as a kind of supplement, which results in a risk to take inappropriate actions. de Craen (2010) demonstrated that the accident risk of novice drivers decreases substantially during the first four years of driving in the Netherlands. In Canada, Mayhew et al. (2003) found that accident rates drop most dramatically during the first six months of driving. Other studies, like (Forsyth *et al.*, 1995), revealed that novice drivers show a pronounced decrease in accident rate after the first years of driving. Considering these previous studies, two periods, i.e. one-year and three-year, are both chosen as the boundary between novice drivers and experienced drivers in this dissertation.

The accumulation of driving experience can lead to more automatic operation in driving. However, the high risk of novice drivers cannot be fully ascribed to the lack of automation, because the task demands can be ‘self-paced’ to decrease the workload. de Craen (2010) referred to Taylor’s ‘self-paced’ theory that novice can overcome the limitations of their performance by using a ‘self-paced’ strategy to reduce their driving speed or to increase following distance. The successful application of ‘self-paced’ requires three proper actions: a) the assessment of their own driving skills; b) the evaluation of the driving task; and c) the execution of driving. In reality, novices are often considered to overestimate their driving skills and underestimating the complexity of the situation when encountering complex situations due to their limited driving experience. Machin and Sankey (2008) investigated the relation between personality factors, risk perceptions, and driver behavior of novice drivers. One important conclusion is that novice drivers underestimate the risks in lots of situations.

Based on these previous studies, it can be concluded that both inexperience and young age have an important effect on driver behavior and are difficult to be separated. As concluded by Groeger (2006), age and inexperience should be associated together to explain the aggressive driver behavior of young novices. There are indications that the lack of experience is more relevant than the young age. In this dissertation, driving experience and driver age are all investigated, and the correlation with driver behavior is also studied.

3. Driving objective and mental state

Some previous studies demonstrated that driver behavior may differ not only between drivers but also for a single driver in different situations. The driver behavior of one driver can vary over time with the change of the driving purposes, the driver's mental state, and external conditions. Actually, the objective of a driver consists of several components: e.g. timely, safety, and comfort. It is generally believed that driving objectives have influence on driver behavior to a certain extent. For example, if the main driving objective is a short driving time, like in a hurried trip, drivers might prefer a higher speed and accept a shorter gap when merging or changing lanes. Whereas, drivers may pursue comfort and behave more modestly in leisure time. The experiments described in (van der Hulst *et al*., 1999) indicated that time pressure causes a increase of aggressive driving behavior. Under higher time pressure, drivers may take a higher speed, choose shorter time headways, and change lanes more often. The influence of driving objectives on driver behavior in China will be identified in Chapter 7.

Driver behavior is also related to the driver's mental state. van der Hulst (1999) carried out experiments in a driving simulator to assess the impact of factors such as attention, intention, anticipation, safety margins, the lack of preview, and driving while fatigued. The study results indicates that drivers often adapt their driving style either when their mental state (e.g. activation or attention level) varies or when prevailing traffic conditions change. van der Hulst *et al. (*1999) presented that drivers could protect themselves from collision by three types of adaptations: operational, tactical, and strategic. However, drivers' competence to adapt became weak during the prolonged driving time. One conclusion drawn from this study is that the combination of fatigue and time pressure is potentially dangerous because the adaptation of driver behavior to these changes is often insufficient for safe driving. The influence of driver's mental state on driver behavior will be taken into account in Chapter 5 (DBQ survey) and Chapter 7 (in-car tests).

3.2.2 Vehicle characteristics

Driver behavior may vary between drivers with different vehicles, especially different vehicle categories. Trucks and buses, having more than four tires touching the pavement, are often referred to as 'heavy vehicles'. Jelenova (2006) presented that vehicle type is strongly related to driver behavior. Compared with passenger cars, heavy vehicles usually have worse operating capabilities than passenger cars, especially concerning acceleration, deceleration, and the ability to maintain speed on upgrades. Individual heavy vehicle's operational characteristics are also associated with the weight of its loading and its engine power. For example, a truck usually accelerates slower than a passenger car; thereby, the truck driver is often characterized with smaller desired accelerations than the driver of a passenger car.

Wenzel and Ross (2005) studied the dependence of driving type on vehicle type and found that the drivers of SUVs and pickup trucks behave more aggressively than the drivers of passenger cars. Aghabayk et al. (2011) found that the driver of heavy vehicles were different from the drivers of passenger cars in lane changing behavior, especially on arterial roads. Therefore he proposed that additional attention should be given to the lane changing behavior of heavy vehicles for model modification.

The specific characteristics of heavy vehicles can be roughly quantified with the term of passenger car unit (pcu). pcu represents the influence on traffic flow imposed by different categories of vehicles. However, the pcu values of the same category of vehicles can vary markedly in different countries, as demonstrated in Chapter 4. It is generally recognized that truck drivers are professional with more experience than most drivers of passenger cars. Therefore, these both indicate that drivers' individual properties play an important role in driver behavior. The study presented in this dissertation mainly focus on Chinese driver behavior in urban areas (explained in Chapter 1) and the comparison with Dutch drivers'. The majority of vehicles in the urban areas in both two countries are passenger cars with the similar size and performance. Thus, the influence of vehicle characteristics on driver behavior is not addressed. The difference in driver behavior between professional and non-professional drivers is investigated by in-car tests, and then analyzed in Chapter 6.

3.2.3 Contextual conditions

During driving, any contextual condition factors which are related to the information perceiving and processing can consequently influence driving behavior. Most of the information related to driving is visual to a driver. The speed with which a driver perceives and processes visible information is directly related to his/her properties. One parameter often used to represent the information perceiving and processing speed is perception-reaction time, which represents how quickly a driver can respond to changes of external conditions (HCM, 2000). The perception-reaction time is associated with external conditions (sight distance, visual field, weather, etc.) as well as personal factors (age, fatigue, experience, etc.). For example, reaction time can vary between daytime and evening. Weather condition is another external factors influencing driver behavior remarkably. Habtemichael *et al*. (2012) compared time headway distributions on a motorway under different weather conditions and found that traffic performance become more variable under medium rain than under other rain intensities. During medium rain conditions, the heterogeneity of driver behavior increases largely. Jiang and Wu (2007) studied the driver behavior in night period and revealed the influence of the driving period on drivers' behavior.

Road geometric design can be utilized as a measure to adjust driver behavior, and furthermore improve traffic performance. The road geometric design mainly includes the geometric characteristics of the facility, such as the number and width of lanes, configuration of bus stations, and curve radiuses, etc. Traffic control including signals and signs is also important to driver behavior, because it can direct a portion of vehicles to slow down or stop (HCM, 2000). de Ridder *et al*. (1999) presented several measures which can reduce traffic volume and speed during a road infrastructure maintenance period. These techniques included colored asphalt pavement, trees and bushes on the medians and road edges, and lampposts.

Benavente *et al*. (2006) demonstrated that driver behavior is remarkably associated with characteristics of the roadway. Aggressive driving behavior relevant to crash involvements is more often observed on arterials roads than on minor roads in urban areas. Based on this study, on a road with more lanes, more often aggressive driver behavior can be observed. Benavente *et al*. (2006) concluded that the presence of curbed medians and curbed road sides can significantly eliminate aggressive driver behavior and reduce the likelihood of crashes. Zwerling *et al*. (2005) explained that drivers may be more attentive on urban roads compared with driving in rural areas because the traffic in city center is more complex with more stoplights, stop-signs, roundabouts, and pedestrian crossings. It was suggested by Zwerling *et* *al*. that the strict enforcement of traffic rules can influence the driver behavior effectively.

Driver behavior can also be influenced by traffic conditions to a certain extent. Drivers may behave riskily and accept short gaps in a congested traffic situation, because they realize larger gaps are less likely to be available. Traffic situations can be distinguished in several regimes, such as free flow, non-congested and congested flow conditions. Driver behavior may change distinctly between regimes. Dijker *et al*. (1998) analyzed the differences in car following behavior between congested and non-congested flow on Dutch freeways. The results show that drivers of passenger cars keep different headways with the change of traffic situations, even at the same speeds. Zhang and Mahlawat (2008) revealed that drivers are inclined to accept very short, unsafe headways when the traffic density is high, i.e. more than 35 vehicles per mile per lane. However when the traffic density is low (less than 12 vehicles per km per lane), there is no relationship between the choice of safe headways and the road environment. The relationship between the driving style and the prevailing traffic condition is not so clear when the density is intermediate (greater than 12 vehicles per km per lane but less than 22 vehicles per km per lane). Jelenova (2006) carried out observations at four intersections to study the correlations between aggressive driving style, gender, age, vehicle status and traffic conditions. But the results of the analysis did not show any evidence about the increase in aggressive behavior with the increase of traffic congestion. Nordfjaern *et al*. (2010) investigated the relations between demographics, personality variables, driver attitudes and behavior in Norway and found that demographic characteristics account more for the differences in driver behavior and attitudes than the traffic environment characteristics.

Based on these previous studies, it can be generally concluded that driver behavior of one driver can vary in terms of his personal factors, vehicle characteristics and contextual conditions. The influence of a variety of factors on driver behavior has been studied in different countries. However, the conclusions are not always consistent with each other. For example, the role of gender in driver behavior was identified differently in several studies. This indicates that drivers in different countries may react differently to the same factor. The mechanism of some factors influencing driver behavior is vague in the available publications. For instance, what is the difference in driving behavior (lane changing, priority giving, etc.) when the personal mental status varies? Most of these previous surveys were carried out in Western countries, and there is not a comparative study of the factors influencing drive behavior made for a developing country. The investigation of driver behavior presented in this dissertation involves most of the factors whose influence on driver behavior has been addressed in the literature. More details are shown in Chapter 5 ~7.

3.3 Influence of Driver Behavior on Traffic Performance and Safety

Traffic flows can be seen as the consequences of interactions among drivers in the traffic stream in a road system. The interaction among vehicles can be represented as headways of car following, gaps for lane changing, and so on. All interactions together determine the state of the traffic flow and traffic performance. For example, an unexpected lane change carried out by one driver may cause a sudden brake of the follower in the target lane and lead to a disturbance to the other drivers. If these drivers react to this disturbance in an inappropriate way, a traffic accident may occur. The studies of the effects of driver behavior on traffic performance and traffic safety found in the literature are presented in this section.

3.3.1 Traffic performance

A thorough understanding of the relationship between driver behavior and traffic performance is significant to practical work, like improving the utilization of the existing infrastructure. The relations between driver behavior and traffic performance can be analyzed from two aspects: traffic flow characteristics and saturation flow rates.

- *Traffic flow characteristics*

In real-life traffic flow, lots of disturbances can be observed, for example a forced lane change, an unexpected brake, etc. It is important whether such a disturbance will grow, or fade away, because this is relevant to the stability of traffic flow (Tampère, 2005). Leutzbach (1988) proposed to distinguish the unstable traffic flow into two types. The first type is called locally unstable if a disturbance from other vehicles only impacts the movement of one following or adjacent vehicle. For the second type 'asymptotically unstable', such a disturbance does not fade away but increases with time and influences a fleet of vehicles. If the disturbance attains to a certain level, the traffic flow will lose stability and break down. The consequence to the traffic performance can be a drop of traffic capacity.

Ossen (2008) considered heterogeneity as an important characteristic of traffic flows. Heterogeneity can be caused by differences in the driver behavior under exactly the same conditions, i.e. the same configuration of road, traffic conditions, and weather conditions etc. Furthermore, the heterogeneity property is relevant to traffic flow stability. The empirical study made by Ossen (2008) demonstrated that the stability of traffic flows are mainly determined by the distances drivers want to keep to the preceding vehicles, and the dynamics characteristics are largely governed by the way in which drivers react to disturbances of the preceding vehicles. Thus, driver behavior can determine the stability and dynamics characteristics of traffic flows to a large extent. The question 'what kind of driver behavior can deteriorate the traffic performance in China' will be studied in this dissertation.

- *Saturation flow rates*

Compared with the properties of heterogeneity, stability and dynamics, saturation flow rates are an easily measured characteristic and can be defined as the maximum flow rate at which vehicles can pass through under prevailing conditions during the green phase. The estimation methods are described in Appendix B, together with an analysis of the merits and limitations of these methods. Some previous researches on saturation flow rates have been carried out in different countries. The study made by Lam (1994) revealed that saturation flow rates at signalized intersections in Hong Kong were smaller than the ones in the United Kingdom. The reasons for these discrepancies were identified to be the differences in the site characteristics and driver behavior between Hong Kong and the United Kingdom.

Hossain (2001) pointed out that traffic characteristics and performance at signalized intersections in developing cities were significantly different from those in developed countries. He studied the saturation flow rates in Dhaka, the capital of Bangladesh, where the prevailing traffic composition was a mixture of motorized and non-motorized vehicles. The research findings demonstrated that the saturation flow rates were lower than the expected values and the existing calculation methods based on the national capacity manual were not applicable to the mixed traffic situation. Leong *et al*. (2006) also made an investigation on pcu and saturation flow rates for through going vehicles at signalized intersections in Malaysia. The research results indicated that the saturation flow rates measured in Malaysia were different from the values calculated based on Highway Capacity Manuals in United States (HCM, 2000). The main cause for the low saturation flow rates in Malaysia was that the traffic composition differs from that in developed countries. Vukanovic *et al*. (1994) studied the capacity of several intersections on arterial streets, collector streets and local streets in the central district of Hangzhou, China and found the main causes for the low saturation flow rates were the mixed traffic (i.e. motor vehicles, pedestrians and cyclists) and permitted conflicts. Through investigating traffic at intersections in Beijing and Shanghai in China, van Zuylen *et al*. (2003) found that the poor signal control design and aberrant behavior of drivers and pedestrians together resulted in an up to 35% reduction in the saturation flow rates of the through going traffic.

These previous studies on saturation flow rates give a consistent indication that the saturation flow rates vary among different countries, and are generally lower in developing countries compared with Western countries. The frequently mentioned causes for low saturation flow rates are the uncontrolled conflicts and the mixture of traffic, which are both common in developing countries. Driver behavior has been shown to influence the traffic performance in an important way, especially in an area with signalized intersections. However, there is not an explicit answer to the question: how to improve the saturation flow rates in countries with such a large proportion of novice drivers, like in China.

In conclusions, every individual driver plays a role in the traffic performance and contributes to the traffic characteristics: heterogeneity, dynamic properties, and saturation flow rates. It is impossible to predict the effect of measures in reality before the influence of every aspect of driver behavior on traffic performance is sufficiently well known. How to measure the influence of aberrant driver behavior on traffic flow? This is the knowledge gap in the present literature. The study presented in Chapter 4 can answer the question.

3.3.2 Traffic safety

In reality aggressive drivers often incline to adopt unsafe behavior, for example red light running, ignoring speed limits, or executing a forced lane change without a sufficient gap. In general, perceptions of risk and personal assessments of emergent situations are relevant to aggressive driver behavior (MacGregor and Slovic, 2000). An inappropriate response of the involved drivers may result in an accident. The aftereffect can be a breakdown in the smooth traffic flow, or even a fatality.

Benavente *et al*. (2006) showed that aggressive driver behaviors is strongly related to crashes that resulted in severe injuries. Al Naser *et al*. (2012) characterized driver behavior according to traffic safety issues and identified speeding, use of mobile phones, not using seat belts, and not giving priority to pedestrians as most dangerous offences in United Arab Emirates (UAE). By observing 201 participants driving along a test route, Risser (1985) revealed the typical drivers errors leading to traffic conflicts, and then classified driver behavior according to the correlation with traffic safety. In this study, the influence of driver age, driving experience on driving behavior was eliminated.

Traffic rules play an important role in traffic management and the communication between drivers. As mentioned by Hauber (1980), the communication during driving includes the use of the indicator, headlights and horn. Risser (1985) also found erroneous communication or the lack of communication is often observed in traffic conflicts. In addition, the way by which road users get used to communication with each other contributes to the driving culture in a city, a region, or a country. Rosenbloom *et al*. (2009) compared the offences against traffic rules at three locations: a big city, a medium sized town, and a village respectively. Besides the factor of gender, driving locations contributed significantly to the driver behavior. The frequency of offences in the town and village areas was higher than that in the city area. The results indicated that drivers comply with traffic rules differently according to the traffic conditions.

The Driver Behavior Questionnaire (DBQ) is a well-documented instrument to obtain self-reported driver behavior and to reveal the relation to accident involvement. Reason *et al*. (1990) divided human risk behavior into errors and offences, and developed a survey instrument, the Manchester Driver Behavior Questionnaire (DBQ), to measure the relationship between self-reported driver behavior and involvement in traffic accidents. It was concluded by many studies that errors and offences both have negative correlation with age and are positively with exposure, and furthermore are strongly related to the accident involvement (af Wåhlberg *et al*., 2011; Bener *et al*., 2008; de Winter and Dodou, 2010; Forsyth *et al*., 1995). In this dissertation, DBQ is used to investigate self-reported driver behavior, to reveal the correlation between behavior and lots of factors, and to identify the difference in driver behavior between Chinese participants and Dutch participants. More details are presented in Chapter 5.

A possible way to simulate the influence of driver behavior on traffic safety is to develop or to modify a traffic model to predict the occurrence of incidents. Time to collision (TTC) is an important time-based indicator for detecting rear-end-conflicts in traffic safety evaluation. Vogel (2003) defined TTC as the distance between two road users or to an obstacle divided by the relative speed. Jin *et al*. (2011) divided TTC into three categories: dangerous situations, relative safe situations, and absolute safe situations, and used the distribution of TTC to assess the traffic safety of an expressway. In order to avoid collisions, drivers need to continuously update the information about the position and behavior of other road users and judge whether it is proper to carry out a certain maneuver (Bachmann *et al*., 2011). Thus, the relations between driver behavior and traffic safety can be represented by TTC.

A laboratory simulation with film segments was used by Hoffmann and Mortimer (1994) to study drivers' ability of estimating TTC. It was found that most investigated drivers were able to properly estimate TTC if the angular speed of the preceding vehicle was larger than 0.003radians/sec. However, the large standard deviation of estimated TTC indicates the possibility of rear-end collisions due to the poor estimation of TTC made by some drivers. Kiefer *et al*. (2006) indicated that TTC was consistently under-estimated during actual driving. It was proposed by van der Hulst *et al*. (1999) that individual differences in the adaptation of driving behavior to changes in the traffic situation should get more attention from researchers.

In short, driver behavior, especially aberrant driver behavior, is proved to be strongly relevant to traffic safety. How to stimulate drivers to develop proper driver behavior which can result in safe and efficient traffic performance in a developing country? This question is not studied thorough in the literature. In Chapter 5, the relation between driver behavior and traffic accidents involvement is investigated by a DBQ survey.

3.4 International Driver Behavior Comparison

The term 'culture' is common in social sciences and humanities. Hoebel (1966) described culture as an integrated system of learned behavior patterns. This system is characteristic of the members of a society instead of a result of biological inheritance. The conventional approach to analyze the influence of culture on driver behavior is to compare the driving style between different countries. In the literature, the methods used for international comparative study of driver behavior can be classified into two kinds: observations of traffic on roads and Driver Behavior Questionnaire (DBQ) survey.

- *Observations of traffic on roads*

Lam (1994) compared driver behavior at urban intersections in Hong Kong with those in the United Kingdom. This research showed that the measured saturation flows and passenger car unit (pcu) values of buses and lorries in Hong Kong are smaller than the ones in the United Kingdom, which implies that there is a distinction of driver behavior in different countries. A comparative study of the capacity and the travel speed was carried out by Wang *et al*. (2007) between Chinese freeways and Dutch freeways. They found that the speed variations in traffic flows in China are larger than those in the Netherlands. Additionally, both the capacity and the speeds on Chinese freeways are lower compared with those on Dutch freeways.

- *DBQ survey*

Compared with observations on roads, Driver Behavior Questionnaire (DBQ) is a more often used tool for the comparative study of driver behavior, owing to the easier collection of a variety of information. DBQ was originally developed for the traffic safety study. In the past twenty years, DBQ became one of the most widely used instruments for measuring driving style. Lajunen *et al*. (2004) made a postal DBQ survey of drivers in Britain, Finland and the Netherlands. The study also analyzed issues related to the cross-cultural influence on the application of DBQ. Even though all three countries in this study were industrialized Western European countries with similar traffic management strategies; differences in driver behavior were still discovered, which can be interpreted as the diversity of culture in these countries.

Bener *et al*. (2008) carried out a DBQ among two Arab Gulf countries: Qatar and United Arab Emirates (UAE). The statistic results showed that UAE drivers scored higher on almost all DBQ items than Qatari drivers. It was concluded that driver behavior varies among different countries due to the diversity of cultural background. Ozkan *et al*. (2006) compared British, Dutch, Finnish, Greek, Iranian, and Turkish drivers' driving skills with the purpose to reveal the relationship between perceptual-motor skills (e.g. fluent driving) and safety skills (e.g. conforming with traffic rules). The survey results demonstrated that the driver behavior varies largely in different countries and the possible reasons can be the variety of culture, distinction in driving testing systems, etc.

Mynttinen *et al*. (2009) carried out a self-assessment combined with a practical driving test in Finland and Sweden to examine whether novice drivers are overconfident with respect to their actual skills. The results indicated the proportion of those who overestimated their competence was greater among the Swedish candidates than the Finnish candidates. The main reason is the more extensive self-assessment training given to drivers in Finland.

A Driver behavior questionnaire (DBQ) survey carried out by Warner *et al*. (2011) aimed at the different driver behavior among Finland, Sweden, Greece and Turkey and the relation between driver behavior and drivers' self-reported accident involvement. The results revealed that different countries have different problems with regard to aberrant driving behaviors which need to be taken into account when promoting traffic safety in practice.

Nordfjaern *et al*. (2011) conducted an international comparative study to investigate the differences in drivers' attitudes to road traffic risks and self-reported driver behavior among Norway, Russia, India, Ghana, Tanzania and Uganda. The analysis results revealed remarkable difference in driver behavior between the high-income and low-income countries. Another cross-cultural study has been carried out by Sivak *et al*. (1989c) for the differences in risk-perception among U.S., Spanish, West German, and Brazilian drivers in 1989. After analyzing the data collected through slide-projected traffic scenes, they found that country and age are two main factors which influence drivers' opinion about risks in driving. Sivak *et al*. exacuted another comparative study in 1989 to investigate differences in self-assessment and risk-taking behavior among U.S., Spanish, and West German drivers. The data were collected through 14 questions and a simulated intersection on a video display. Country, age, and gender were presented as singnificant factors accounting for the difference in self-assessment and risk-taking behavior (Sivak *et al*., 1989a; b).

A limited number of studies on international driver behavior comparison give consistent indications that driver behavior and the traffic characteristics in different countries can be rather distinct. Despite the impersonal causes, such as traffic management strategies and traffic composition, etc., different culture is demonstrated to be an important reason to interpret the diversity of driver behavior. However, no further comprehensive study with respect to the role of culture on driver behavior has been found at present. Lack of attention to this issue can obscure the efficient approach to improve driver behavior in reality.

3.5 Summary

The literature review of driver behavior focuses on several key points: the relations of driver behavior to human factors, vehicle characteristics and surrounding conditions, the influence of driver behavior on traffic performance, and the international driver behavior comparison. This section summarizes the relevant knowledge found in the literature, the implications for the study in this dissertation, and the knowledge gaps existing in the literature.

- *Knowledge summary and implications for the present study*

In the literature, a variety of factors have been shown accountable for the diversity of driver behavior in reality (introduced in section 3.2). Even though the conclusions drawn from different studies are not always consistent with each other, the most important factors are still highlighted for the research conducted in this dissertation. The investigation data for representing the individual characteristics of the driver should comprise aspects as: driving experience, aberrant driver behavior, reaction time, speed and acceleration profiles, response to designated traffic situations, decision-making mechanism in driving, etc. In this dissertation new insights into irregular driver behavior will be obtained based on the empirical data collected in China and the Netherlands. Some factors will be constrained and are not involved in study. For instance, the driving weather and driving regions are both kept similar in every test trip.

Traffic performance can be characterized as heterogeneity, stability and dynamics, etc. Saturation flow rates are a frequently adopted indication for traffic performance at intersections. A consistent conclusion can be drawn from the previous studies that saturation flow rates are strongly related to the local driver behavior and traffic conditions. This study will also investigate and compare saturation flow rates at intersections. According to the literature review, driver behavior is strongly related to traffic safety (introduced in section 3.3.2). A popular method to analyze the correlation between aggressive behavior and traffic incidents involvement is through a DBQ survey, which has been widely applied in the literature. In this study, traffic accidents involvement will also be studied by DBQ.

Several driver behavior investigation methods have been introduced in the literature review, such as: DBQ, observations on field, in-cat tests, laboratory simulator, etc. However, the advantages and limitations of these investigation methods have not been addressed explicitly. The surveys of driver behavior in this dissertation will be conducted by observations on roads, a DBQ survey, in-car tests and focus group sessions. The additional attention will be paid to the verification of research results obtained from different data sources.

- *Knowledge gaps*

Overall, the main limitation of current studies is insufficient research on national driver behavior, even it has been confirmed that driving culture and traffic conditions in developing countries both significantly differ from those in Western countries.

The literature review shows that differences exist in the behavior of different drivers, but it is not clear how large and how important these differences actually are, especially among different countries.

Very limited research has been done for the link between aberrant driver behavior and simulation models. Driver behavior can be simulated in various models to reproduce the traffic. Some irregular behavior, e.g., offences, is difficult to model. This gives discrepancy between the simulated results and reality if the errors or aggressive behavior in driving are often excluded in the simulation models. It should be doubted whether these simulation models reflect the real, actual driver behavior, especially when they are applied in developing countries, like China.

Attitudes towards driving are not sufficiently addressed in the literature. Driving attitudes can directly impact driver behavior, as well as representing the driving culture and custom. This dissertation will investigate drivers' attitudes to driving by DBQ surveys and focus group discussions.

In conclusion, the state-of-the-art draws the general research conclusions for research on characteristics of driver behavior, provides the implications for the study in this dissertation and also reveals the knowledge gaps. In this dissertation, Chapter 4 presents a comparative study of saturation flow between China and the Netherlands, which is strongly related to the traffic performance. Chapter 5 compares the self-reported driver behavior in China and that in the Netherlands. In Chapter 6 and 7, further investigation and analysis of driver behavior are carried out for Chinese drivers. Chapter 8 applies the investigation data and results to calibrate a simulation model. The research presented in this dissertation is expected to answer the questions presented in Chapter 1 and fill in the knowledge gaps revealed in this chapter.

Chapter 4

Comparative Study of Saturation Flow[2]

4.1 Introduction

As introduced in Chapter 2, the rapid development of transport in China is based on the fast progress of urbanization and motorization, and is characterized by high growth speed in an enormous scale. Chinese driver behavior is linked to such a national transport development stage. The unbalance between traffic supply and traffic demand has worsen in urban areas due to the limited public space and the high traffic volume. Since the urban space and financing for road construction are both restrained, it becomes crucial to enhance the utilization of the present infrastructure. This chapter gives an insight into the characteristics of saturation flow at signalized intersections in urban areas, as a starting point for the study of Chinese driver behavior.

In an urban road network, intersections are the conflict points between different traffic flows. The performance of intersections, especially the signalized intersections is critical to the efficient use of an urban road network. Elevated roads and ring roads usually do not have signalized intersections, but sometimes still have metering signals for the accesses. The study made by Zheng (2011) illuminated that travel times in urban cities are determined by traffic control, saturation flow rates and desired speeds. In many cities, the poor performance of signalized intersections is one of the causes of severe congestion. The congestion at an intersection is often ascribed to the insufficient traffic capacity: too much traffic and deficient capacity. Another possible reason can be inappropriate traffic control: too much time is lost and the space of the intersection is not efficiently used. A further reason might be that the drivers do not make full use of the available green time. In this case, the actual saturation flow can be considered as suboptimal. Therefore, the performance of a signalized intersection is mainly determined by the ratio of traffic volume to road capacity, traffic control, and the behavior of road users.

[2] This chapter is based on the paper: Comparison of driver behaviour and saturation flow in China and the Netherlands (2012), by Li J., H. J. van Zuylen, Y. S. Chen and R. H. Lu. *IET - Intelligent Transport Systems,* 6 (3): 318-327.

Two previous studies focused on the remedies for serious congestion in Beijing and Shanghai respectively (Chen and van Zuylen, 2002; van Zuylen *et al*., 2003). They found that the inappropriate signal control at the ramps was the main cause of the congestion in the ring roads in both two cities. The saturation flow rates were found to be especially low compared with the values measured in a Western country, the Netherlands. They concluded that most existing microscopic simulation models are not valid for direct application in China and should be calibrated and validated for the specific local conditions. Consequently, these studies revealed the importance of a further study on driver behavior and simulation models application in China.

In summary, the efficiency of an urban road network is strongly related to the performance of signalized intersections where the ratio of traffic volume to road capacity, traffic control, and driver behavior are three determining factors. Saturation flow rates are an important indication of the performance at a signalized intersection. This chapter presents a comparative study of the saturation flow between Chinese cities and Dutch cities with the following research objectives:

1. To reveal the difference in the characteristics of saturation flow at signalized intersections between two countries;
2. To explore causes of the inefficient traffic performance;
3. To reveal the contribution of driver behavior to the traffic performance;
4. To identify the influence of traffic control on saturation flow.

The Netherlands was selected as the reference country due to its typical characteristics of a developed European country and the convenience in investigation. The next section introduces some previous studies on the saturation flow. Section 4.3 introduces the saturation flow rate estimation methods used in this chapter. In section 4.4, the results of the saturation flow survey in five cities are presented and the comparison between two countries is made. The plausible causes accounting for the low saturation flow rates at Chinese intersections are presented in section 4.5. The implications for traffic control design and simulation program modification are analyzed in Section 4.6 and Section 4.7. In the last section, main findings and conclusions of this chapter are summarized.

4.2 State-of-the-Art of Studies on Saturation Flow

Some previous studies have been done on the traffic flow characteristics in different countries. Vukanovic *et al*. (1994), Hossain (2001), van Zuylen *et al*. (2003), and Leong *et al*. (2006) carried out empirical studies on saturation flow at signalized intersections in developing countries: China, Bangladesh, Malaysia respectively. Some details have already been written in Chapter 3. A consistent conclusion drawn from these studies is that the saturation flow rates and the corresponding capacity of the investigated intersections were lower in developing countries than those in Western countries. The reasons for the low saturation flow rates were revealed as: the mixed traffic and permitted conflict. According to the comparison with the intersections at United Kingdom, Lam (1994) ascribed the low saturation flow rates in Hong Kong to the differences in geometric patterns and driver behavior. A study carried out by Wang *et al*. (2007) focused on the capacity and the travel speed on freeways. The results demonstrated both the capacity and the speeds in Chinese freeway were lower compared with those in Dutch freeways. Although Wang *et al.* did not study urban roads; the results they found are rather similar to the conclusions made in other studies.

Beside the saturation flow rates, passenger car unit (pcu) of different types of vehicle in developing countries also differed from the values measured in Western countries (Hossain, 2001; Saha *et al.*, 2009). Hossain pointed out that the existing calculation methods or western-developed simulation models were not applicable to the developing countries where the prevailing traffic composition was mixed traffic.

Rahman *et al.* (2005) executed a study to measure the saturation flow rates at signalized intersections in Yokohama (Japan) and Dhaka (Bangladesh). The comparison results indicated that the saturation flow rates in the Dhaka metropolis were slightly higher than those in Yokohama, which is inconsistent with most previous studies. The possible reason was that only two intersections in Dhaka were investigated in this study and the data sample was also too limited.

The limited studies on international comparison of traffic flows give a consistent indication that the saturation flow in developing countries is rather irregular, which is a cause of the reduction in road capacity. The performance of a signalized intersection can be specifically represented by the saturation flow characteristics: saturation flow rate, start lag/ end lag, headway distribution, and speed, etc. The performance of signalized intersections is mainly determined by traffic control, upstream and downstream traffic situations, drivers' behavior and other external factors, e.g., lane width, traffic composition, vehicle performance, weather, etc. Traffic control is a crucial factor to intersection performance because inappropriate traffic control can result in large lost time to the subject intersection, and can also lead to upstream and downstream disturbances. A scheme is made to illustrate the factors that influence saturation flow, as shown in Figure 4.1.

Based on the literature review, the past efforts on saturation flow were mainly contributed to saturation flow rate estimation methods, the influence of locations or weather characteristics, and traffic composition. The other significant factors influencing the intersection performance are the uncontrolled conflicts and the mixture of traffic, which are both common in developing countries. At present, trucks and motorcycles are forbidden running in the arteries in the daytime in lots of Chinese big cities. Thus the traffic composition in these areas is already quite similar to that in the cities of Western countries. Are the characteristics of saturation flow, like saturation flow rates and start lags still quite different from those in Western countries? Very few studies address this issue.

The complex relationship between saturation flow and the related factors is clearly shown in Figure 4.1. Since it is impossible to investigate all of these factors in one chapter, the highlighted factors in bold type are addressed in this study.

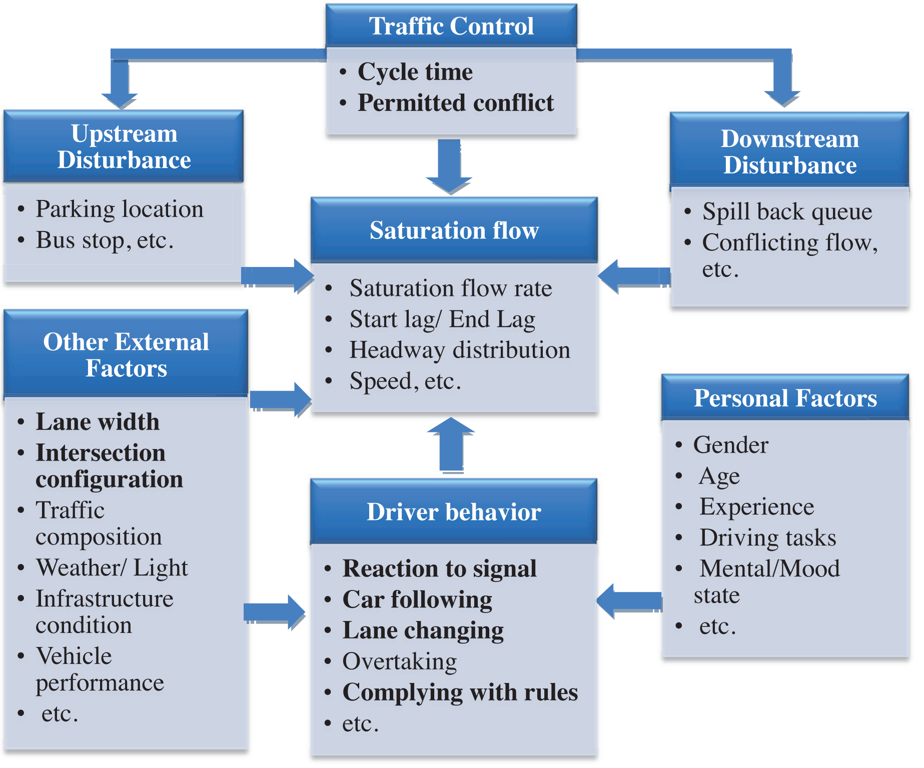


Figure 4.1 Scheme with the main factors influencing saturation flow characteristics
Note: Factors in bold will be studied in this dissertation.

This chapter presents the comparative study of saturation flow characteristics at intersections between Chinese and Dutch cities. The data were collected by video observations. In order to make the intersections more comparable, the investigated intersections are selected in terms of the following uniform factors:

- *Similar traffic composition;*
  Most vehicles were passenger cars (>90%), a small proportion of buses and trucks in Chinese and Dutch intersections respectively.
- *Similar investigation time;*
  All videos for the investigated intersections were made at peak hours of working days.
- *Similar weather conditions;*
  Good weather, without rain in the investigation period.
- *Similar infrastructure conditions;*
  Flat intersections, similar lane width, more details in Section 4.5.1.
- *Without disturbance;*
  Without disturbance from parking locations, bus stops, spill back queues, conflicting flow, etc.

- *Exclusive lanes for vehicles;*
  Separated from bicycles, motorcycles, and pedestrians.

The main difference between the investigated intersections is traffic control. All of Dutch intersections have vehicle actuated signal control, while the Chinese intersections have fixed time control. In the following sections, the characteristics of saturation flow at intersections in two Dutch and three Chinese cities are investigated.

4.3 Methodologies of Saturation Flow Rate Estimation

Intersection geometry, traffic volume, saturation flow rates, lost time, signal control type and traffic composition are the basic parameters for the intersection signal control design. The saturation flow rate is the maximum flow rate at which vehicles can pass through under prevailing conditions during the green phase. Start lag, i.e. start-up lost time, is a part of the lost time, which is defined in Highway Capacity Manual (HCM, 2000) as '*the additional time, in seconds, consumed by the first few vehicles in a queue at a signalized intersection*.' Passenger car unit (pcu) is the ratio of the time needed for a certain vehicle category passing the designated location to the time needed for a normal passenger car, which accounts for the speed and space occupancy ratio of a special vehicle to a passenger car. In the literature, pcu also named PCE (passenger car equivalent) (HCM, 2000).

The saturation flow rates are strongly associated with signal control and management design. Stokes (1988) presented a brief review of studies on the estimation of saturation flow rates at signalized intersections. He emphasized that engineers and planners should be prudent to collect local data to estimate the saturation flow rates for capacity studies, because the saturation flow rate is sensitive to the prevailing local conditions.

Methods commonly used for estimating saturation flow rates fall into two groups, namely the formula method and local measurement method. The formula method is usually introduced by a capacity calculation manual, like HCM (2000), and is intended for the prediction of the capacity based on characteristics of the lanes, traffic conditions etc. The formula is based on a partly heuristic and partly analytical model, taking into account lane width, slope, probability of conflicts etc. It is often recommended that saturation flow rates should be measured in field to reflect the local traffic conditions, but that is time consuming. In this section, a short introduction will be given to HCM formula method and local measurement method, which are both frequently referred to in literature. Some additional analysis is presented in Appendix B.

1. HCM Formula

The formula method for estimating saturation flow rates is based on the use of the base saturation flow rate (ideal maximum traffic flow rate) which is adjusted by a variety of factors to reflect the local prevailing conditions (Stokes, 1988). Although, manuals for signalized intersection analysis often recommend the use of local measured saturation flow rates (HCM, 2000), it is impractical to measure saturation flow rates of a new intersection still under construction. In this case, saturation flow rates can be estimated by a saturation prediction formula which includes a set of parameters to represent the local traffic conditions.

A typical saturation flow rate calculation formula is introduced in Chapter 16 of HCM (2000). The formula begins with the default base saturation flow rate 1900 pcu/h/ln and the number of lanes in the lane group. Prevailing traffic conditions are taken into account as 11 adjustment factors. Most of these factors are indicated in Figure 4.1. According to (HCM, 2000), a saturation flow rate for each lane group is computed with the following function:

$$s = s_o\, N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} \qquad (4.1)$$

where

s: saturation flow rate for the subject lane group, expressed as a total for all lanes in the lane group (veh/h);

s_o: base saturation flow rate per lane (pcu/h/ln);

N: number of lanes in a lane group;

$f_w \sim f_{Rpb}$: a series of adjustment factors which can influence saturation flow rates in reality.

HCM is the most widely accepted document for the analysis of the capacity of signalized intersections and freeways. In the world, lots of countries have modified the formula introduced by the HCM to develop their own national standard for saturation flow prediction, like in China (GB50647-2011, 2010).

2. Field measure method

The methods to measure saturation flow rates in field can be classified into three groups: the headway ratio method, regression method and Product Limit Method (PLM). Headway ratio method has been used by Lam (1994), Anand *et al*. (1999), Rahman *et al*. (2005), Leong *et al*. (2006), (Joseph and Chang, 2005) and Saha *et al*. (2009), etc.. In the literature review, the headway ratio method is the most frequently used method, however it can't be used to estimate start lag and end lag. van Zuylen and Li (2010) introduced Product Limit Method (PLM) which uses the information both of unsaturated and saturated flow conditions and can estimate the probability distribution of saturation flow rates (more details in Appendix B). PLM is considered a little more complicated and not used as often as the other two methods in practice. The regression method has been developed by Branston and van Zuylen (1978) and is considered as a simple and valid way to calculate saturation flow rates, pcu values of manly types of vehicles, start lag and end lag at the same time. In this study, the regression method was used to measure and compare the traffic characteristics between Chinese and Dutch intersections.

The regression method requires that the measured traffic flow should be saturated during the observation periods; i.e. only the previously queued vehicles are involved. The fully saturated period should be divided into several time intervals in which the number of vehicles passing the stop line and the vehicle types are both counted. If a fully saturated time interval does not start at the beginning of the green phase or end at the end of the green phase, the number of passenger cars passing in a time interval with length T can be counted as:

$$n = s.T - p_1.n_1 - p_2.n_2 - p_3.n_3 - \ldots \qquad (4.2)$$

where

s: the saturation flow rate,

n: the number of passenger cars,

n_1: the number of busses,
n_2: the number of lorries,
n_3: the number of articulated lorries,
p_1: the pcu value of buses,
p_2: the pcu value of lorries,
p_3: the pcu value of articulated lorries.

By counting the passing vehicles n, n_1, n_2, etc. in different time intervals T, the parameters s, p_1 , p_2, p_3 etc. can be estimated by linear regression (Branston and van Zuylen, 1978).

If the time interval starts at the beginning of the green phase, the start lag should be taken into account by subtracting an effective green time from the first time interval. Figure 4.2 illustrates how to transform the effect of initially slow-moving vehicles into a start lag λ_1.

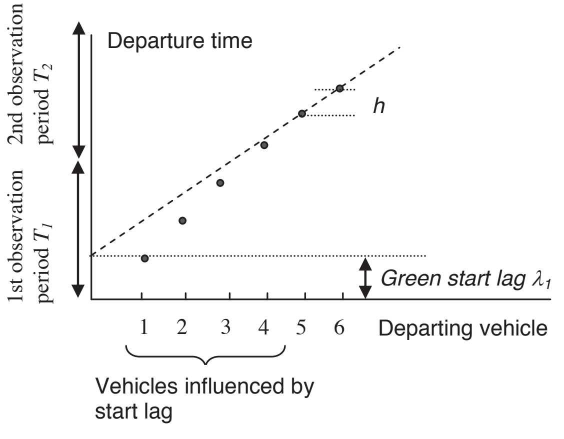


Figure 4.2 The definition and formation of the start lag

If the flow is fully saturated, the number of vehicles discharging in the last time interval of the green phase might be larger because vehicles still can pass in the first seconds of the yellow phase. This can be taken into account as an extension of the green phase with an end lag λ_2.

Therefore the number of passenger cars that pass during a time period of T can be expressed with a more complete formula:

$$n = s\,T - p_1\,n_1 - p_2\,n_2 - p_3\,n_3 - b\,X_1 + e\,X_2 \quad (4.3)$$

where

$X_1 = \lambda_1\,s$
$X_2 = \lambda_2\,s$
$b = 1$ for time intervals at the beginning of the green phase and otherwise $b = 0$;
$e = 1$ for time intervals ending at the start of the yellow phase, i.e. a traffic queue still remains during the whole observation time period T, and otherwise $e = 0$.

All parameters s, p_i and X_i can be determined by linear regression from observations. It should be kept in mind that Function (4.3) with $e = 1$ is only applicable for observations in time periods with a fully saturated flow. The time intervals which include new arrival vehicles without waiting in the initial queue will be filtered from the saturation flow analysis.

4.4 Comparison of Saturation Flow Characteristics

In this study, video cameras were used to record traffic flow at peak hours on working days for four intersections in the Netherlands and four intersections in China. All observed lanes had protected green phases and only used by motorized traffic without side parking and bus blockage, so that slow road users (bicycles, pedestrians etc.) and other disturbance did not have an influence on the vehicle movement. On average, data were collected for every lane group for more than 30 signal cycles. Details of the observations are described in (Lu, 2009).

4.4.1 Saturation flow rates

In this study, saturation flow rates are estimated both with the HCM formula and the regression method. For the HCM formula method, 11 factors are determined based on the local traffic conditions. Especially the lane width, approach grade, area type, left and right turning factors are chosen according to the field traffic situation. As a comparison benchmark, the saturation flow rates estimated by the HCM formula have been compared with the values measured with regression method in the field. The comparison results are shown in Table 4.1.

Table 4.1 Comparison of average saturation flow rates estimated with different methods

City	Road	Lane Group[a]	Average Saturation Flow rate (pcu/h/ln)		$S_f/(S_{HCM})$
			Field (S_f)	HCM(S_{HCM})	
Chengdu [CH]	Dongchenggen	LT	1753	1697	103%
		TH	1417	1786	79%
	Babaojie	LT	1671	1715	97%
		TH	1507	1805	83%
Beijing[CH]	Fuchengmen	TH	1557	1590	98%
Changsha[b] [CH]	Furonglu_North 2008b	LT	1472	1679	88%
		TH	1468	1767	83%
	Furonglu_North 2009	LT	1522	1679	91%
		TH	1461	1767	83%
	Furonglu_South 2009	LT	1495	1679	89%
		TH	1632	1767	92%
Delft [NL]	Zusterlaan	LT	1946	1704	114%
	Kruithuisweg	TH	2317	1862	124%
		LT	2208	1769	125%
Hague [NL]	Koningskade	TH	1958	1729	113%
		RT	1812	1470	123%
	Boslaan	TH	1959	1843	106%
		RT	1890	1567	121%

[a] *Letters denotes approach lane group: TH, through lane; LT, exclusive left-turn lane; RT, exclusive right-turn lane.*
[b] *This approach has been observed twice, first was in 2008 and the second time was in 2009. They are denoted as FuR._N 2008 and FuR._N 2009 respectively.*

The results shown in Table 4.1 are consistent: most saturation flow rates estimated at Chinese intersections, except for the left-turn lanes at DongChengGeng in Chengdu, are lower than the HCM2000 values by 3%-21%. On the contrary, the saturation flow rates in the Netherlands are all higher than the HCM values, varying from 6% to 25%. In Table 4.2, the difference in saturation flow rates and the standard deviations (SD) of the left-most through lanes are shown as a more detailed example.

Table 4.2 Comparison of average saturation flow rates of left-most through lanes

Nation	City	Intersection	Saturation Flow rate (pcu/h/ln)	SD (pcu/h/ln)
China	Chengdu	Dongchenggen	1509	74
		Babaojie	1457	94
	Beijing	Fuchengmen	1378	187
	Changsha	Furonglu_North2008	1291	59
		Furonglu _North2009	1436	37
		Furonglu _South2009	1547	65
the Netherlands	Delft	Kruithuisweg	2429	35
	The Hague	Koningskade	1982	201
		Boslaan	2084	316

The average saturation flow rate of the left-most through lanes at Dutch intersections is 2165 pcu/h/ln, and is much higher than the average value of 1436 pcu/h/ln at Chinese intersections. In Table 4.2, it also can be found that the standard deviations of saturation flow rates at Dutch intersections are also higher than those at Chinese intersections. Figure 4.3 is drawn based on Table 4.2 and reveals the difference in saturation flow rate between two countries clearly.

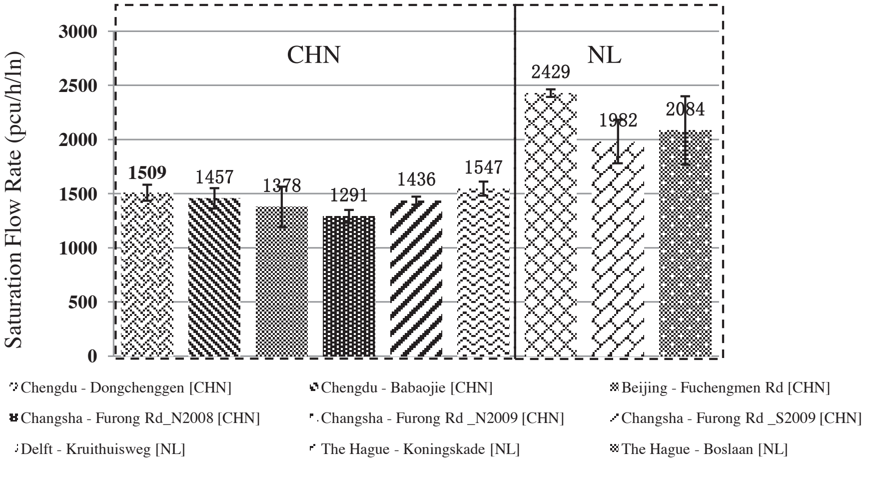


Figure 4.3 Comparison of average saturation flow rates of left-most through lanes

Generally, the investigated Chinese intersections had fixed time signal control with long cycle time and high, even over saturated traffic volumes. On the contrary, the investigated Dutch intersections were all actuated controlled with low traffic volumes and short cycle time. High traffic volumes and long saturated periods are the plausible reasons for the low standard deviations of saturation flow rates of the left-most through lanes at the Chinese intersections.

4.4.2 Time headway comparison

The time headway, as an important characteristic of the driver behavior, is the time interval between one vehicle and its preceding vehicle passing the same stop line. The recorded time of the vehicle is the rear axle passing the stop line in this study. The time headway of the first vehicle is the time interval between the start of the green phase to the first vehicle's real axel passing the stop line. The analysis of the time headway gives a significant indication of pcu values (Kimber, 1985), although it gives a biased estimation of the saturation flow rate (Bonneson *et al*., 2006). Habtemichael *et al*. (2012) indicated that time headway provides the comprehensive image of traffic stability and driver behavior under a certain traffic condition.

Figure 4.4 illustrates the average time headways and the standard deviations. The average time headways in China were about 2.5~2.9 seconds, almost 20~30% longer than those in the Netherlands. Furthermore, the standard deviations of the time headways in China were also larger than those in the Netherlands. The long time headway of cars in China indicates that the Chinese drivers tend to keep large distances from the preceding vehicles or tend to keep low speeds in passing through the intersections. The low standard deviations of the time headways reflect the more homogenous characteristic of the saturation flow in the Netherlands than those in China.

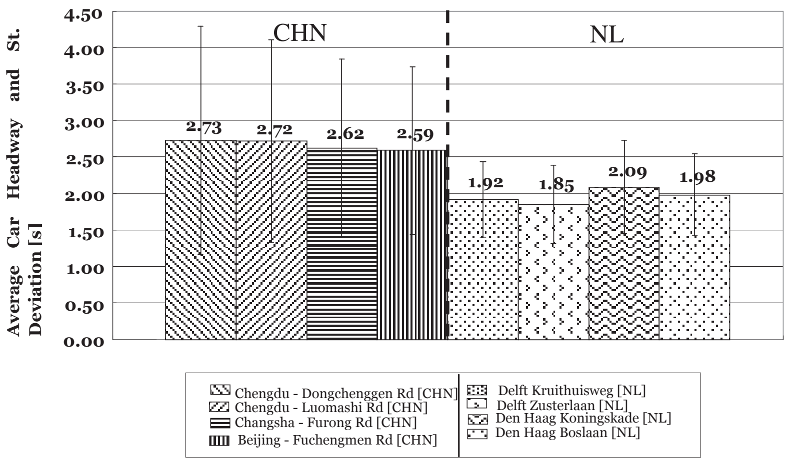


Figure 4.4 Average Time headways and Standard Deviations

The average time headways of the first four vehicles are shown in Figure 4.5. The data were collected from the through going lanes. The time headways at Chinese intersections were remarkably larger than those observed at the Dutch intersections. The variance in time headways at these Chinese intersections was also significantly higher than what observed in the Netherlands.

It is clearly illustrated in Figure 4.5 that the time headways decrease with the vehicle discharge progress. At the investigated Dutch intersection Koningskade, time headways became stable after the second vehicle. The larger time headway and the higher variance period at the investigated Chinese intersections were significant indications for the lower saturation flow rate and larger start lag, compared with the Dutch intersections.

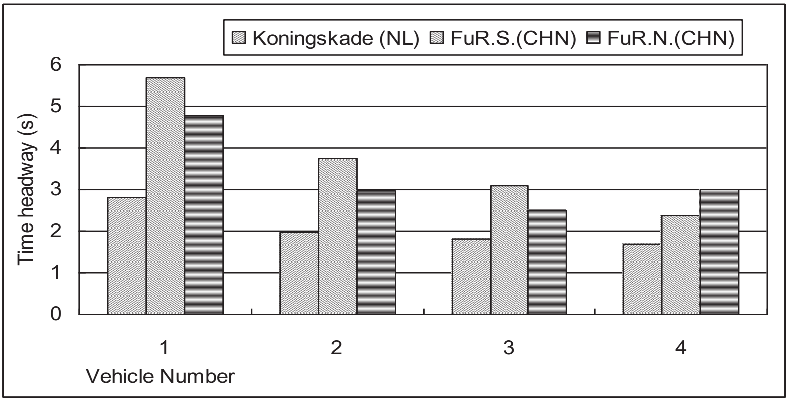


Figure 4.5 Headways of the first 4 vehicles at three intersections

4.4.3 Start lag comparison

The number of vehicles that can pass the intersection in a green phase is also related to the start lag and end lag. The start lag results in a lost time at the beginning of a green phase. Because of the reaction time of the driver and the acceleration time of the vehicle, the first few vehicles take relatively more time to pass the stop line than the following ones. At the end of the green phase, an extension of the phase can be observed because vehicles continue to discharge during the yellow phase. The restriction on saturation flow observations excludes time intervals with under-saturated flow. In this study, there were very few green phases observed with fully saturated flow lasting to the yellow phase. Therefore, end lags were not analyzed and compared.

van Zuylen *et al*. (2003) reported that the start lag was between 4 and 6 seconds at the investigated Chinese intersections. More information about the start lag in China is expected to be attained in this study. In order to develop the regression Function (4.3), every cycle time was split into two parts. The first part includes the first few discharging vehicles which are assumed to experience the start lag. If the headways in the remaining part of the green phase are stable, the saturation flow rate can be accurately estimated. An underestimation or overestimation of the number of vehicles suffering from start lag will both bias the estimation of start lag and saturation flow rate.

In order to find out the number of vehicles that were affected by the start lag, the first time period T_1 in every observed cycle was set with different length including 2 to 9 vehicles. When the number of vehicle included in the first period was changed, the start lag and saturation flow rate estimated by regression function (4.3) would be different, even though all of the other data were kept as the same. The empirical relation among start lag, saturation flow rate and number of vehicles included in the first observation period is shown in Figure 4.6. Two lanes were selected as examples and described with solid line and dashed line respectively. The horizontal axis indicates the number of vehicles included in the first time intervals of the cycle. The vertical axis represents the estimated saturation flow rates (left) and start lags (right). The number of vehicles influenced by the start lag in reality should be the point where the start lag and saturation flow rate both achieve the maximum value. In Figure 4.6, the numbers of vehicles suffering from the start lag in these two investigated lanes can both determined as 6.

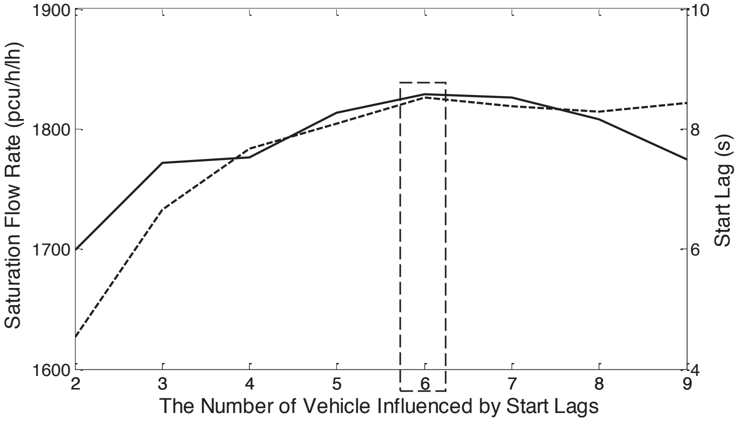


Figure 4.6 The number of vehicle influenced by start lags and saturation flow rates

The comparison of start lags between the two countries is shown in Table 4.3. The start lags at all the Netherlands intersections were lower than those in the Chinese ones, except the left-turn lanes. Most of the Netherlands start lags were between 1 and 2 seconds, which were close to the previous study results reported in HCM (2000). The number of vehicles influenced by the start lag in the investigated Dutch lanes was rather low, only varied between 2 and 3. On the contrary, the start lags measured on the lanes in China were much higher than the ones measured in the Netherlands, even beyond 8 seconds on some lanes. The vehicle number influenced by the start lag varied between 4 and 6. To summarize, Table 4.3 indicates that Chinese drivers lose more time at the beginning of a green phase and more vehicles suffer the start lag than those at the intersections in the Netherlands.

Table 4.3 Comparison of start lags at the Chinese and Dutch intersections

City	Intersection[a]	Lane[b]	Start Lag (s)	Number Influenced Vehicles	R^2
The Hague (NL)	Koningskade	TH_L	1.8977	3	*0.92398***
		TH_R	2.4696	3	*0.80831***
		RT_L	1.4978	3	*0.78759***
		RT_R	1.7496	3	*0.85922***
	Boslaan	TH_L	2.3109	2	*0.99759***
		TH_R	2.1274	2	*0.86168***
		RT_L	1.2233	3	*0.96273***
		RT_R	1.1883	2	*0.98237***
Changsha (CN)	FuR.L_N.2009	LT_L	1.3839	2	*0.97755***
		LT_R	0.7688	2	*0.95738***
		TH_L	3.5965	4	*0.99187***
		TH_M	2.7329	3	*0.98075***
	FuR.L _S.2009	LT	2.4635	2	*0.90077***
		TH_L	6.7625	6	*0.98735***
		TH_M_L	7.0114	5	*0.99597***
		TH_M_R	6.7103	5	*0.86508***
		TH_R	8.4847	5	*0.99328***
	Bayi.L._E.	TH_L	4.7875	5	*0.9725***
	Bayi.L._W.	TH_L	5.6648	5	*0.88246***
		TH_R	3.0862	4	*0.89202***

Note: [a] *N, S, E and W denote the approach north, south, east and west respectively.*
[b] *Letters denote approach lane group: TH_L, left through going lane, etc.*
*** means p value is smaller than 0.01.*

In order to prove that the estimated saturation flow rates and start lags for two countries are significantly different, Wilcoxon rank sum test is used to check the null hypothesis that two datasets are independent samples from identical continuous distributions with equal medians. Test result $h= 1$ indicates a rejection of the null hypothesis, and $h = 0$ means a failure to reject the null hypothesis at the 5% significance level. The test results in Table 4.4 prove that the saturation flow rates and start lags of these two countries are not from the same continuous distributions and the mean values are also different at a significance level less than 5%.

Table 4.4 Wilcoxon rank sum test results

Datasets	*p*-value	*h*	Date source
Average saturation rates on through lanes	0.0122	1	Table 4.1
Average saturation rates on turning lanes	0.0159	1	Table 4.1
Average saturation rates on left-most through lanes	0.0238	1	Table 4.2
Start Lags	0.0122	1	Table 4.3

Compared with saturation flow investigated in the Netherlands, the low saturation flow rates, large variance in time headways, and long start lags are the main characteristics of Chinese saturation flow. The investigation results require a further analysis of the inefficient green phases, heterogeneous driver behavior and long lost time at Chinese signalized intersections.

4.5 Analysis of Low Saturation Flow Rates Causes in China

This section identifies the causes which are ascribed to the low saturation flow rates, large variance in time headways, and long start lags at Chinese intersections. As explain in Section 4.4, the eight investigated intersections were all not close to a parking lot or a bus stop. Left-turn flows were all exclusive and without the influence of a permitted conflict traffic stream (all intersections have protected left-turn phases). The reasons for the special characteristics of saturation flow low at Chinese intersections are analyzed from several aspects: lane width, traffic control scheme, intersection configuration, and driver behavior. In Figure 4.1, these influence factors are highlighted by bold words.

4.5.1 Influence of lane width

Wider lanes may have higher saturation flow rates and larger capacity. Based on the Chinese urban road design standard, 3.25 m is the minimum lane width of urban roads when the design speed is not larger than 60km/h (CJJ37-2012, 2012). However, the lane width at most Chinese intersections is generally reduced from about 50m upstream from the stop line in order to increase the number of lanes at the intersections. Thus, the lane width at the approaches of intersections in China is similar to that in the Netherlands. The average lane width of the four investigated roads in China is 3.075m; while this value in the Netherlands is 3.175m. In order to verify whether the narrow lanes can explain the difference in saturation flow, the relation between lane width and saturation flow was analyzed, as shown in Figure 4.7.

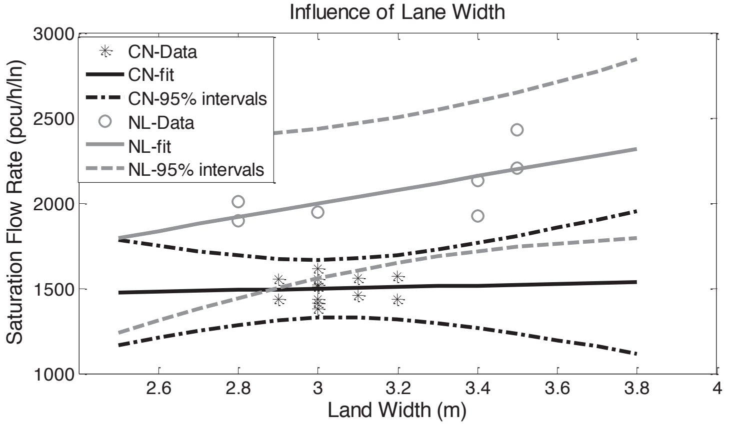


Figure 4.7 Dependence of saturation flow rates of the lane width with 95% confidence intervals

The probability is small that the lower saturation flow rates at Chinese intersections can be explained by the difference in lane width, as shown in Figure 4.7. It is also difficult to find any distinct relationship between the lane width and the saturation flow rate at the Chinese intersections (R^2 = 0.00336, whereas for the Dutch intersections R^2 =0.45093).

4.5.2 Influence of the traffic control scheme

All the investigated Dutch intersections were vehicle actuated control; the Chinese intersections were fixed time control. Besides the difference in the signal control strategy, the main differences in signal control design between Chinese and Netherlands intersections were: clearance time, cycle time length, and right-turn flow control. At most Chinese intersections, three seconds yellow time were used as the whole clearance time, without extending the clearance time by an all-red transition time for the large size intersections. The cycle time of Chinese signalized intersections was quite long compared with that of Dutch intersections. Furthermore, right turning in red phase was allowed at most Chinese intersections. This paragraph analyzes the influence of these three factors on the saturation flow at Chinese intersections.

1. Control scheme design

When one traffic flow stops, safety requires some clearance time before a conflicting stream of traffic is allowed to enter the intersection (Muller *et al*., 2004). The time interval when no vehicle is permitted to enter the intersection is named inter-green or clearance time. Clearance time is calculated by the time T_1 minus the time T_2. T_1 is the driving time for a vehicle from the stop line to the end of the conflict area. T_2 is the time spent by another vehicle from the next green phase to accelerate from the stop line to the beginning of the conflict area. In practice, the clearance time is achieved through green time transition intervals, which can include yellow, all-red time or both. All of the investigated Chinese intersections had a quite large size with fixed yellow time of 3 seconds without an all-red transition. So it was rather common to find conflicting vehicles blocking the traffic flow at the beginning of a green phase. Conflicting traffic can increase the start lag and reduce the lane capacity. In previous studies, typical observed values of start-up lost time range from 1 to 2 seconds in Western countries. The start lags of Chinese intersections estimated in this study were much larger than the expected values, as shown in Table 4.3.

2. The effect of countdown timers

In order to improve the capacity and safety of intersections, countdown timers are installed at some signalized intersections to indicate the time remaining (in seconds) for present phase in some Chinese cities. The countdown timer is expected to stimulate drivers starting fast at the beginning of the green phase and to reduce the start delay consequently. During the green phase, the drivers can also get time-related information from countdown timer which may help them to make proper decisions, such as decelerating or accelerating.

In the literature, lots of studies regarding the application of countdown timer have been published. One similar conclusion made from these studies is that countdown timer has a positive but generally limited impact on the capacity of signalized intersections, even the start-up lost time is confirmed to be reduced (Kidwai *et al*., 2005; Limanond *et al*., 2009; Liu *et al*., 2012; Rijavec *et al*., 2013). Besides decreasing start-up lost time, Sharma *et al*. (2009) and Liu *et al*. (2012) showed that countdown timer can evidently shorten time headway at the end of a green phase in India and China respectively. Very few studies gave the different conclusion: the installation of a countdown timer can dramatically increase the intersection capacity on account of the better utilization of the yellow time, the reduction both in start-up delay and saturated headways (Chiou and Chang, 2010; Long *et al*., 2013; Ma *et al*., 2010).

From the traffic safety view, a countdown device is controversial owing to speeding up in yellow phase and the consequent increase of the dilemma zone length, even the red running violation rate is reduced (Chiou and Chang, 2010; Limanond *et al*., 2009; Ma *et al*., 2010; Rijavec *et al*., 2013).

In this survey, at the intersection named Bayilu in Changsha countdown timers have been installed. However, the saturation flow rate at this intersection was only 1491(pcu/h/ln); the start lag was still around 6 seconds and the number of vehicles influenced by the start lag was about 5. The observations of the video show that at the beginning of the green phases there were still around four conflicting cars and three pedestrians in the conflict area at this intersection. Therefore, the installation of such a timer alone does not significantly improve the saturation flow rates if the clearance time is still insufficient. An appropriate cycle time including sufficient clearance times is expected to reduce the start lag for the intersections in Changsha city, China.

3. The influence of long green phases

There are some previous studies (van Zuylen *et al*., 2003) indicating that the headways in the saturated green phase may increase when the green phase is longer than 40 or 50 seconds. That means that longer green phases may not be as efficient as shorter phases. In this study, most Chinese intersections had a cycle time longer than 120 s and the observed lane groups' green phases were usually longer than 50 s. The investigated Dutch intersections were all vehicle actuated signal controlled with varying cycle time. The green phases of observed lane groups were also much shorter than the Chinese ones.

In order to analyze the influence of long cycle time on the efficiency of saturation flow, the saturated green time is divided into time intervals of 5 s. For every time interval, the average time headway is calculated. The reciprocal of the average headway can be considered as an approximation of the average value of saturation flow rates (as explained in Appendix B). In Figure 4.8, the horizontal axis is the green time; and the vertical axis represents the saturation flow rates calculated from the average time headway. At all of the studied intersections, the saturation flow rates keep increasing from the start of green phase. After 20 seconds, the saturation flow rates become stable. At around 40 seconds, there are small drops that are much smaller than the ones found in other research (van Zuylen *et al*., 2003). At the end of the green phase, the saturation flow rates will have a slight rise, which can be found both at Chinese and Netherlands intersections. In summary, the low saturation flow rates in China cannot be attributed to long cycle time of Chinese intersections.

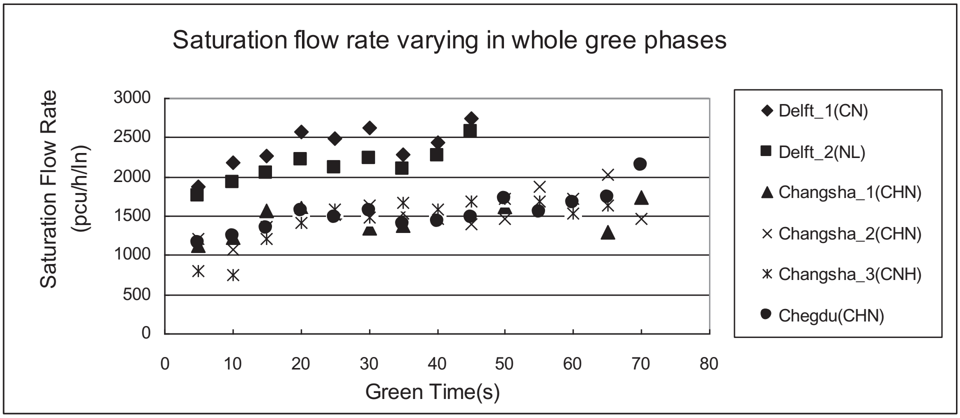


Figure 4.8 Average saturation flow per 5 seconds time interval during green phases

At all investigated intersections, the saturation flow rates keep increasing from the start of a green phase. After 20 seconds, the saturation flow rates become stable. At around 40 seconds, there are small drops that are much smaller than the ones found in other research (van Zuylen *et al*., 2003). At the end of the green phase, the saturation flow rates will have a slight rise, which can be found both at Chinese and Netherlands intersections. In summary, the low saturation flow in China cannot be attributed to the long cycle time of Chinese intersections.

4. The influence of the intersection configuration

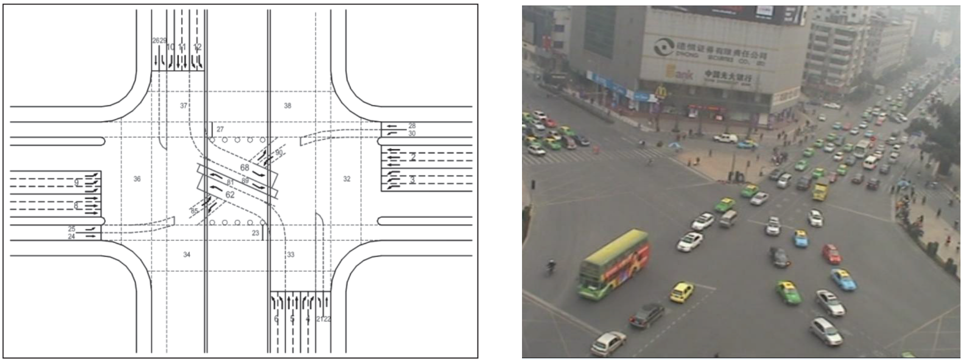
In Chinese cities, buffer space is marked to improve the left-turn capacity at many large signalized intersections, as shown in Figure 4.9. Usually, the buffer space consists of one or more lanes extending from the stop line to the center of an intersection. Left turning vehicles can line up in the buffer space until their (exclusive) signal turns green.

Compared with the Dutch left-turn saturation flow rates, Chinese values are significantly lower, as shown in Table 4.1. However, at the same approach of the Chinese intersection, the left-turn saturation flow rates are slightly larger than those of the through going lanes.

There are plausible reasons to account for the high saturation flow rates of left-turn lanes at Chinese intersections:

1. The exclusive left-turn stream has a large turn radius at large intersections. Thus, the influence of turning on the speed becomes trivial.

2. Buffer space provides space for left turning vehicles to overtake each other and to fan out, as shown in Figure 4.9.



(a) (b)

Figure 4.9 Layout of buffers for the left-turn flow (a) and the implementation in Chengdu (b)

The configuration of the FuRong Lu (FuR.L) intersection in Changsha was redesigned with buffer space at the end of 2008. Investigations had been made twice for this intersection: first time (without buffer space) was in 2008 and second time (with buffer space) was in 2009. The difference in saturation flow rates between these two years are shown in Table 4.1. The buffer space improves the left-turn saturation flow rate from 1472 to 1522 pcu/h/ln, whereas the through lane saturation flow rate still remains approximately the same as before. The first five vehicle's time headways decrease visibly after the introduction of the buffer space. The start lag and number of vehicles influenced by the start lag also decreased in 2009 compared with the values in 2008; more details are shown in Table 4.2. It can be concluded that a buffer space can reduce the start lag and the number of vehicle influenced by the start lag, and accordingly improve the saturation flow rate.

4.5.3 The impact of offences and conflict vehicles

Offences against traffic rules are quite common at Chinese intersections. More detailed introduction and analysis can be found in Chapter 5~7. The most frequently observed offence is the sudden lane changing by crossing a solid marking line near the stop line. Such behavior disturbs the normal traffic flow and consequently reduces the saturation flow rate. However, this aberrant behavior is rarely observed at the intersections in the Netherlands. As analyzed in Section 4.5.2, the result of an insufficient clearance time is that conflicting vehicles still remain in the conflict area at the beginning of the next green phase. Offences against traffic rules and conflict traffic both can be considered as a kind of disturbance to the protected traffic flow in the green phase.

For one intersection in Chengdu, the influence of traffic offences and conflict traffic on saturation flow rates has been modeled by adding two variables q_1 and q_2 to the regression saturation flow function (4.3)

$$n = s\,T - p_1\,n_1 - p_2\,n_2 - p_3\,n_3 - q_1 m_1 - b\,(q_2\,m_2 + X_1) + e\,X_2 \qquad (4.4)$$

where

m_1: the number of offences against traffic rules which influence the normal traffic flow

q_1 : the influence factor of offences against traffic rules

m_2: the number of conflicting vehicles which still stay at the intersection at the start of a green phase

q_2: the influence factor of non-cleared vehicles

When the Function (4.3) is used to estimate the saturation flow rate for the left through going lane in Chengdu, the saturation flow is 1509 pcu/h/ln, and the start lag is 3.11s. When the influence of non-cleared vehicles and offences against traffic rules are both taken into account, the estimated value of saturation flow rate increases from 1509 to 1573 pcu/h/ln and the start lag falls from 3.11s to 1.86s. Through regression calculation, the values of q_1 and q_2 are 0.33 and 1.41 respectively. More details are shown in Table 4.5.

The interpretation of the influence factor q_1 of non-cleared vehicles can be that:

Every conflicting vehicle still staying in the conflict area at the start of the green phase will reduce 0.3316 vehicles passing the stop line.

The influence factor q_2 of traffic offences represents that:

Every offence can block 1.41 vehicles.

Table 4.5 Influence factors of offence and conflict vehicles on saturation flow rates

Results	**Saturation flow rate (s)**	**Start lag (λ_1)**	p_1	n_1	q_1	m_1	q_2	m_2
With adjustment	1573	1.8583	1.9381	8	1.4062	54	0.3316	13
Statistic test	R^2: 0.972; F: 297.92; P: 0; error variance: 2.8386							
Without adjustment	1509±74	3.1107	1.8771	8	-	-	-	-
Statistic test	R^2: 0.96491; F: 430.770; P: 0; error variance: 3.8976							

Based on this analysis, inappropriate driver behavior is an important reason for the low saturation flow rates in China. For instance, an arbitrary lane change and overtaking can directly disturb the protected traffic flow. Furthermore, most drivers have to be always alert to possible aberrant behavior of other drivers and are inclined to keep long gaps and low speeds even in a strict traffic management situation. This attitude has been confirmed by the driver behavior focus group discussion introduced in Chapter 7.

Another possible reason is that a large proportion of Chinese drivers have a short driving experience, especially compared with drivers in Western Countries. The number of drivers increases in China by about 10% per year. Some novices tend to keep longer gaps and to drive at lower speeds compared with experienced drivers. More details are explained in Chapter 2.

4.6 Implications for Traffic Control Design

At signalized intersections, the appropriate traffic signal design should provide sufficient green time to every traffic flow and limit the total lost time. Based on the study introduced in Section 4.4 and Section 4.5, two important implications can be made for the traffic control design in China:

- *Parameter values in traffic control design should be calibrated for the local traffic situation.*

Saturation flow rates and start lags (delays) are important parameters in traffic control design for both an individual intersection and coordinated intersections. The default values of these two parameters in the program manuals are usually calculated based on the driver behavior in Western countries. In China, the actual saturation flow rates are lower and start lags are much longer than the default values. If these parameters are not calibrated for the local traffic situation, it is impossible to make appropriate traffic control design in practice.

- *Sufficient clearance time should be introduced into cycle time calculation.*

Based on the analysis made in Section 4.5, the main flaw in traffic control design at Chinese intersections seems to be the insufficient clearance time which markedly increases the start delays. Generally, the clearance time should be long enough to prevent accidents, but not longer than what required for clearing away the conflicting traffic. The length of clearance time depends on the distance of the entering and exiting streams from conflict areas and the vehicle characteristics, i.e., speed and acceleration (Muller *et al*., 2004). The clearance time calculation is also relevant to the sequence in which traffic streams appear in the cycle.

If the required clearance time after phase i is $t_{c,i}$, the average number of conflicting vehicles appearing at the intersection at the start of the next green phase $i + 1$ is $t_{c,i} \times v_i$, where v_i is the flow volume i [veh/s]. If the influence factor of non-cleared vehicles is 0.33, as q_2 deduced in Table 4.5, these conflicting vehicles will increase the start lag in the next green phase with $0.33 \times t_{c,i} \times v_i / s_{i+1}$ seconds (s_{i+1} is the saturation flow rate of the next phase) for every lane. In the next green phase, the total reduced effective green time will be $n \times 0.33 \times t_{c,i} \times v_i / s_{i+1}$, where n is the number of lanes affected by the non-cleared vehicles.

If an all-red phase is introduced to extend the clearance time, the required all-red time is $t_{c,i}$, namely the additional lost time $t_{c,i}$. Therefore, the question of whether the saturation flow rate of this lane group can be improved by introducing an all-red clearance time has the answer:

- *YES, if* $0.33 \times n \times v_i / s_{i+1} > 1$ *or* $v_i > 3 \times s_{i+1} / n$ [veh/s].

Such a flow rate can be likely observed when there are more than three lanes influenced by the non-cleared vehicles in the next green phase $i + 1$.

Summarily, a control scheme without an all-red clearance time will be more efficient if there are less than 3 lanes suffering from the influence of conflicting vehicles, even though this control is more risky. Otherwise, introducing a sufficient clearance time will improve the performance and safety for the whole intersection.

In conclusion, the study of saturation flow is critical to traffic control design. Unexpected low saturation flow rates and long start lags should be sufficiently considered in the traffic control design for Chinese intersections. The introduction of an appropriate clearance time into the signal control design can not only reduce the start-up of the green phase, but also give drivers more confidence when passing an intersection. Consequently, a sufficient confidence in driving will lead to a higher saturation flow rate.

4.7 Implications for Simulation Programs

In practice, simulation programs are often used to analyze traffic situations, to evaluate the effect of traffic control design and the impact of other ITS measures. The calibration of these models is often carried out on the level of traffic volume, traffic composition, vehicle characteristics and network configuration, in most cases not on the level of driver behavior (Chen and van Zuylen, 2002; van Zuylen *et al*., 2003). This approach cannot ensure the consistency between simulation results and the reality. Traffic measures that are effective for driver behavior in Western countries might be completely ineffective or even counterproductive for Chinese situations, and vice versa. The simulation results will not be reliable without calibration and validation for Chinese driver behavior.

The negative impact of the lack of clearance time can be simulated in a micro-simulation program by introducing conflicts at the signalized intersections at the beginning of the green phase. Modeling such conflicts for an intersection is not necessary if the clearance times are long enough. A simpler way to represent this effect of insufficient clearance time in simulation model is to increase the start-up delay or to reduce the effective green time according to the values estimated in the previous section.

Summarizing, the micro-simulation programs that are developed and calibrated for Western countries have to be adapted for Chinese conditions by:

- A modified car following model, including a larger reaction time, a lower free-flow speed, more cautious in following;
- Desired acceleration, deceleration and desired speed should be calibrated according to Chinese driver behavior, especially in intersection areas;
- An adaptation of the lane changing model to represent a mixture of hesitating, aggressive and aberrant behavior;
- The representation of remaining conflicts during the green phase due to insufficient clearance time;
- Classification of driving style based on the heterogeneous characteristic of saturation flow.

These suggestions for models adaptation and calibration draft a plan for the further research reported in the following chapters. The driving style categorization based on the survey data is presented in Chapter 6. The correlation between driving type and observed driver behavior is also described in Chapter 6. The calibration for the desired acceleration and deceleration functions in a microscopic model is introduced in Chapter 8.

4.8 Conclusions

A thorough investigation of saturation flow at signalized intersections was carried out in three Chinese cities and two Dutch cities. Some important conclusions can be drawn based on this comparative study:

- *Low saturation flow rates at Chinese intersections:*

The utilization of lanes in Chinese cities is 20–30% less than that in the Dutch cities and is also lower than the 'standard' saturation flow rates calculated according to the formula in HCM (2000), which is based on the average North-American traffic situations.

- *Buffer space at intersections:*

The introduction of buffer space can increase the saturation flow rates for the left-turn traffic, but potential risk to traffic safety is also found.

- *Large start lags at Chinese intersections:*

The start lags measured at the intersections in China were much higher than those in the Netherlands, even larger than 8 seconds on some lanes. The number of vehicles influenced by the start lag in China varied between 4 and 6, which was also larger than what people expected before.

- *Heterogeneous driver behavior in China:*

The average values of saturation time headway in China were 20-30% longer than those in the Netherlands, with much larger standard deviations. These investigation results indicate that the Chinese drivers tend to keep large distances from the preceding vehicles or to keep low speeds in intersection areas. The large standard deviations of the time headways reflect a heterogeneous driver behavior in China.

- *Causes are identified for the low saturation flow rates at Chinese intersections:*

Traffic offences and the insufficient clearance time are identified as important reasons for the low saturation flow rates at Chinese intersections. Traffic offences and the remaining of conflicting vehicles both disturb the traffic flow protected by green phases. The lack of all-red clearance time increases the start lag, especially when there are more than three lanes suffering from the conflicting vehicles.

The findings from the saturation flow survey have important implications for practice in Chinese cities. The performance of the intersections in Chinese cities is not so well and the saturation flow rates are lower than those in the Netherlands. This fact is surprising on one hand and possible to be improved on the other. The pressure on the urban road network is high in Chinese big cities. According to the analysis of the survey results, remedies for the low saturation flow rates and long start lags are:

- To emphasize driver training/education with disciplinary and regular driving behavior,
- To improve the control of intersections and reduce remaining conflicts by introducing sufficient clearance times,
- To modify the intersection geometry, for example, by introducing buffer space for left turning vehicles.

The causes of low saturation flow rates in China, i.e. inefficient traffic control and aberrant driver behavior, may also be found in other developing countries. Therefore, the conclusions obtained from the current study can be applied to other countries, even though they are based on a comparison just between China and the Netherlands. An improvement of road capacity with 20 to 30% cannot solve the traffic problems in a sustainable way since it just counteracts the growth of traffic for 1 to 3 years (see Chapter 2). The capacity improvement is still important because it can benefit both the urban road traffic performance and traffic safety.

The saturation flow investigation results illustrate that the urban traffic situation in China is different from that in North America and Western Europe. The instruments for traffic management and road design have to be adapted for Chinese traffic characteristics: low saturation flow rates, long start lags, and unexpected disturbance from the aggressive lane changing or overtaking. The thorough calibration and validation of simulation programs requires detailed data collected in China. This requirement for the detailed data motivates the elaborate surveys of driver behavior, as introduced the Chapter 5~7. The application of investigation results for model calibration is the main topic of Chapter 8.

Chapter 5

Driver Behavior Questionnaire Survey[3]

5.1 Introduction

The comparative study presented in Chapter 4 reveals the differences in saturation flow characteristics at signalized intersections between Chinese cities and Dutch cities. Compared with the intersections in the Netherlands, The Chinese ones were characterized as low saturation flow rates, large variance in time headways, long start lags. The inefficient saturation flow at the Chinese intersections can be attributed directly to different driver behavior, and indirectly to the inappropriate traffic control design. These conclusions motivate comprehensive surveys of driver behavior in China.

Human factors in driving can be separated into two parts: driving skills and driving style, which both contribute to driving behavior (Elander *et al*., 1993). Driving skills (including the information processing and the maneuver executing) can be improved with the accumulation of driving experience. The driving style is the way a driver chooses to drive and is related to individual driving habits. After several-years driving experience, drivers can develop a driving style which can be influenced by the whole driving culture. Tasca (2000) pointed out that driver behavior is also *the result of the norms, rewards, punishments and models to which individuals have been exposed and can be partly culturally transmitted*. Even if this opinion has been generally accepted, the research is limited on two aspects: which cultural factors can influence driver behavior and to what extent the influence can be.

In order to get an insight into the role of culture in driver behavior development, it is necessary to carry out a comprehensive study of driving behavior. As a further and continued study of Chapter 4, a series of surveys of driving behavior has been carried out in China, including a Driver Behavior Questionnaire (DBQ) survey, in-car tests and focus group sessions. The comparative study of self-reported driving behavior between China and the Netherlands is expected to answer the following research questions:

[3] This chapter is partly based on the paper: The Driver Behaviour Questionnaire: An investigation study applied to Chinese drivers (2014), by Li J., H. J. van Zuylen and E. van der Horst, In *Computer-based Modelling and Optimization in Transportation: Advances in Intelligent Systems and Computing*, 262: 433-447.

- Is there a remarkable difference in self-reported driver behavior between China and the Netherlands?
- How to develop an indication from DBQ answers to represent driving style?
- What factors can influence driver behavior significantly?
- What measures can be identified for the improvement of driver behavior in practice?

This chapter includes six sections. Section 5.2 is a state-of-the-art of the studies on DBQ survey and the cross-culture comparison of driver behavior. Section 5.3 presents the questionnaire design and the survey procedure. The following section 5.4 reveals some results from a further statistical analysis. Section 5.5 presents the factor analysis results and detects which factors are strongly related to driver behavior. Section 5.6 discusses the consequences of the specific behavior of Chinese drivers to the traffic performance. Some important conclusions and recommendations for the future study are also presented.

5.2 State-of-the-Art of Studies on Driver Behavior Questionnaire

Driver behavior, as a critical component to traffic safety and traffic performance, has drawn abundant attention from researchers over decades. The investigation methods for driver behavior study mainly consist of questionnaire surveys, focus group discussions, in-car tests, simulation, video observations etc. Every investigation method has some advantages and some limitations as well. For example, simulation can construct an imitation of a real traffic surrounding in order to capture the detailed driver behavior in the simulator, but the validity of the simulation results are often suspected. As implemented in Chapter 4, making a movie to record the traffic performance can collect objective traffic data in reality, also with the limitations of short observation periods and specified road sections. The other three investigation methods which have been used in this dissertation are introduced in Chapter 5, Chapter 6 and Chapter 7 respectively.

As introduced in Chapter 3, the Driver Behavior Questionnaire (DBQ) is one of the most widely used instruments for measuring self-reported driving behavior. The study on drivers' aberrant behavior initiated by Reason et al. (1990) is considered as a turning point for the research on self-reported driver behavior. In view of the human contribution to accidents, Reason *et al*. (1990) made a distinction between errors and violations, because these two forms of aberration may have different psychological origins and require different modes of remediation. Three fairly robust factors: violations, dangerous errors, and relatively harmless lapses, were identified by analyzing the DBQ from 520 drivers. Due to the different psychological mechanisms, violations can be the result of social and motivational factors, whereas errors (slips, lapses, and mistakes) may be accounted by the information-processing characteristics of the individual driver. The version of DBQ developed by Reason is named as Manchester DBQ, and has been referred by many subsequent studies.

In the following twenty years, a variety of DBQ surveys have been carried out worldwide. Lajunen *et al*. (2004) reported that DBQ studies have been done in Australia, China, Greece, Finland, the Netherlands, New Zealand, Sweden, and Turkey. The aim of most of the DBQ studies in literature was to investigate the relationship between driving behavior and the involvement of accidents. As Bener *et al*. (2008) concluded, the most general findings made by these previous studies are:

- Women and old drivers usually commit violations less frequently than men and young drivers;
- Female and old drivers commit more errors than male and young drivers;
- The more frequently drivers drive, the more often they offend traffic rules.

There are several studies related to DBQ surveys made in China. Luo and Chen (2008) made a DBQ survey for 114 drivers and found that aggressive driver behavior is strongly related to traffic accidents. Based on a survey of self-reported drivers behavior in China, Zhang *et al*. (2009) explored a method to analyze the driver characteristics quantitatively. Similar to the DBQ study made in other countries, a two-dimension factor structure was established to describe the driver's conscious and unconscious behavior by means of factor analysis. Shi *et al*. (2010) studied driver behavior through both a paper survey (134 participants) and an internet survey (431 respondents). The found on-road driving experience, rather than the level of driving training and age, is the crucial to the driver behavior in China.

In addition to domestic research on driver behavior, DBQ has also been applied in international comparative study of driver behavior. Lajunen et al. (2004) found the DBQ four-factor structure was congruent for Finland and the Netherlands, but not as perfect as for Britain. Ozkan *et al*. (2006) carried out a DBQ study in Europe and concluded that both external factors (e.g., traffic culture) and internal factors (e.g., age and gender) can significantly influence the driver behavior. Bener *et al*. (2008) compared DBQ scores between drivers in Qatar and United Arab Emirates (UAE) and found that UAE drivers scored higher on almost all DBQ items than Qatari drivers. Goszczynska and Roslan (1989) made a study of self-judged driving skills in relation to other drivers both in Sweden and in the United States. Although drivers differed in cultural background, the outcomes of this study still confirmed that a majority of drivers overestimate their own driving skills. Mynttinen et al. (2009) carried out a DBQ to study the difference in driver behavior between Finnish and Swedish drivers. Warner et al. (2011) made a cross-cultural study to compare the difference in drivers' aberrant driving behavior in four countries: Finland, Sweden, Greece and Turkey. The important conclusions drawn in these researches have been introduced in Chapter 3. The most consistent findings made from these studies are:

- Drivers from higher income countries reported safer attitudes regarding driving after drinking, obeying priority rules, seat belt using, etc.;
- Drivers from lower income regions reported more willing to take risks in driving, but more precautious to other drivers in conflict areas.
- The differences in driver behavior are generally in line with the traffic management systems, driving training and license systems.

In conclusion, various versions of DBQ with different data collection methods (e.g. postal survey, road-side survey) for different sampling targets (e.g. professional drivers, elderly drivers) have been applied in many studies. The most common research objective is the relation between driver behavior and traffic safety. However, neither the comparison of driving behavior between China and Western countries through a DBQ survey, nor a DBQ study focusing on the influence of driver behavior on traffic performance has been carried out before. The survey introduced in this chapter is intended to fill in this blank.

5.3 Methodology

5.3.1 Questionnaire Design

Manchester DBQ is a worldwide instrument for studying driver behavior. Almost in every study, the questions in DBQ were modified in terms of the specified study objectives (af Wåhlberg *et al*., 2011; Davey *et al*., 2007; Motevalian *et al*., 2011; Wishart *et al*., 2006). In order to match the objective of this study, a new DBQ was designed with 50 items based on previous versions (Bener *et al*., 2008; Davey *et al*., 2007; Lajunen *et al*., 2004; Wishart *et al*., 2006). In international comparative DBQ studies, the veracity in translation is of particular importance, because a slight discrepancy in translation can result in diverse understanding by respondents. In this study, DAQ was made in three languages: Chinese, English and Dutch. The translators for three languages together made the necessary corrections and modifications. An overview of the DBQ survey is introduced in this section.

This questionnaire starts with some demographic questions (e.g. age, gender) and some basic questions about driving (e.g. driving frequency, driving skill). Table 5.1 shows the questions and results in details. Most of the previous Manchester Driver Behavior Questionnaire (Lajunen *et al*., 2004) included 24 items for aberrant driver behaviors. Due to the different research objectives, the items related to aberrant driver behaviors in the current study have been reduced to 14 items. In addition, 16 new questions are added based on the research objective, i.e. the influence of driving behavior on traffic performance. These questions are about some typical driving behavior, namely reaction to traffic signals, lane changing, and overtaking. For every items, respondents were asked to estimate the frequency they committed the error on a five-point scale (1=Never, 2= Nearly Never, 3= Seldom, 4= Sometimes, 5= Often), or to choose the level of likelihood that they executed the maneuver (<10%, 10%~40%, 40%~60%, 60%~90%, >90%), according to their driving experience. Table 5.2 lays out the details about these 30 items related to driving behavior in the questionnaire. In addition, there are four questions related to priority rules. Respondents were asked to indicate the meanings of the priority signs, and their attitudes to the conflict flow at intersections, etc. More details about the DBQ can be found in Appendix C.

5.3.2 Procedure and respondents

The questionnaire was published in the internet in February 2013 in China (Li and van Zuylen, 2013) and the Netherlands (van der Horst *et al*., 2013). Respondents were all volunteers and gave their answers online individually. To reduce motivation for socially desirable answers, respondents were explained that DBQ survey in different countries is expected to reveal the problems in traffic system, and to improve traffic safety and efficiency. The answers could remain anonymous. Respondents were instructed to read all questions carefully and to answer each question based on their own driving experience. Until July, 2013, 215 Chinese drivers and 175 Dutch drivers finished the online questionnaires. Samples were representatives from a large geographical area of both countries. The characteristics of the Chinese and Dutch samples are presented in Table 5.1.

The average age of the respondents was similar in these two countries, but Dutch respondents had much longer average driving experience than the Chinese counterparts. The proportion of male respondents was higher in Chinese sample than that in the Dutch sample, i.e. 80% versus 58.3%. Such high proportion of male respondents is consistent with the large share of registered male drivers in China. In 2008, the percentages of registered male drivers and female drivers in China were 84.27 and 15.73 respectively (Cai, 2010). If gender is a significant factor to driver behavior, the disparity in gender proportion between two countries will affect the comparison results. Therefore, special attention should be paid to the relation between driver behavior and gender.

Table 5.1 Characteristics of the Chinese and Dutch samples

Item	**Chinese (*n* = 215)**	**Dutch (*n* = 175)**	**Note**
Mean age (SD)	36.01 (8.05)	39.95 (17.62)	
Male (%)	80.0	58.3	
Mean driving experience in years (SD)	6.19 (6.33)	19.54 (16.91)	
Enjoy driving (SD)	6.92 (2.14)	7.91 (1.52)	1= dislike; 10 = enjoy very much
Self-estimated driving type (SD)	3.95 (2.08)	5.14 (1.80)	1 = very conservative; 10 = very aggressive
Others-estimated driving type (SD)	4.25 (2.14)	5.19 (1.93)	1 = very conservative; 10 = very aggressive
Offences recording in last year (%)	57.7	34.3	
Accidents involved in previous 5 years (%)	51.2	13.1	

Most of the Chinese respondents had less than 5 years' experience (54.4%), which is consistent with the reality: one third of drivers in China have less than 3 years' driving experience (see Chapter 2). In this study, 54.3% of Dutch respondents had more than 10 years' driving experience. About the question: do you enjoy driving, the answer varies from 1 to 10. The answer 1 indicates 'dislike' and 10 means 'enjoy very much'. As shown in Table 5.1, Dutch respondents enjoyed driving more than their Chinese counterparts in terms of the average values 7.91 vs. 6.92.

In the China sample, the percentage of respondents who considered themselves as very conservative, somewhat conservative, and moderate in driving were almost the same: 30.7, 30.0, and 30.2 respectively. Whereas in the Netherlands quite large percent (44.0) of the respondents indicated that they are moderate drivers. According to the average scores of driving type, Chinese respondents were more prudent than the Dutch respondents (3.95 vs. 5.14). Is the self-estimated driving type consistent with the driving style in reality? This should be confirmed through a further data analysis.

There was no remarkable difference between the self-estimated and others-estimated driving style in both two countries. A significant difference existed in the offences recording and accidents involvement between two countries. The percentages of respondents who had the registered traffic offences in the last year were 57.7 and 34.3 in China and in the Netherlands respectively. Only 6.9% of the Dutch respondents had been registered traffic rule offences for 3 times or more, while this value was 20.0% for Chinese sample. Furthermore, more than half of Chinese respondents (51.2%) had been involved in accidents in the past five years, versus a much lower proportion (13.1%) for the Dutch sample.

5.4 Results

The DBQ in this study includes 30 items related to driving behavior and 4 additional questions about the abidance by priority rules. The survey results and the statistical analysis are presented in this section.

5.4.1 Measurement of aggressive driving style

In the first part of the questionnaire, the respondents were asked to estimate their driving style and indicate what do other people think about their driving style on the scale from 1 to 10 (1 = very conservative and 10 = very aggressive). The answers have been shown in Table 5.1. In order to verify these answers, respondents were asked to indicate how often they had each of the 30 driving behaviors or made the mistakes in the previous year. The answers are given on a five-point scale (for frequency: 1=Never, 2= Nearly Never, 3= Seldom, 4= Sometimes, 5= Often; for likelihood: <10%, 10%~40%, 40%~60%, 60%~90%, >90%). Every option for every item is assigned an aggressiveness score from 1 to 5. The higher the score gets, the more aggressive the driving style is. For example, 'Crossing stop-line during the red phase' has five options: Never, Nearly Never, Seldom, Sometimes, and Often. These answers have the corresponding aggressive scores: 1, 2, 3, 4, and 5 respectively. With respect to the italic items in Table 5.2, the high frequency indicates more conservative. For instance, the answer 'never' for the item 'Searching priority signs when close to an intersection' can get aggressive score 5; and the answer 'often' can obtain the score 1. The average aggressive scores, the standard deviations and the differences between two countries in every item are all shown in Table 5.2.

Table 5.2 Investigation results of the DBQ

Items (in short)	CN		NL		Score *Diff*	*h*
	Score	SD	Score	SD		
Priority rules						
1. Searching priority sign when close to an intersection	2.94	1.23	1.42	0.70	**1.52**	1**
2. Giving priority to the vehicles from an arterial street	1.90	0.94	1.05	0.24	0.85	1**
3. Giving priority to through going vehicles	1.76	0.76	1.12	0.38	0.64	1**
4. Giving priority to pedestrians on a zebra	1.74	0.82	1.23	0.46	0.51	1**
Reaction to signal						
1. Crossing the stop line during the red phase	1.83	1.10	1.62	0.82	0.21	0
2. Crossing the stop line during the yellow phase	2.46	1.07	3.73	0.87	**-1.27**	1**
3. Almost being hit by the following car due to the sudden brake in yellow time	1.90	0.98	1.33	0.61	0.57	1**
4. Attention distracted when waiting in red phase	2.29	1.03	1.99	0.82	0.30	1*
5. Almost colliding with the preceding vehicle due to the preceding car's sudden braking in yellow time	2.10	1.05	1.42	0.70	0.68	1**
Car following						
1. So close to the preceding car that would have a collision in the case of emergency	2.10	0.88	1.93	0.88	0.17	1*
2. Becoming impatient to follow a slowly moving vehicle and try to change a lane as soon as possible	3.00	0.99	2.87	**1.05**	0.13	0
3. Changing lanes as soon as possible when following a big truck	2.62	1.06	3.42	**1.14**	**-0.80**	1**
Lane changing						
1. Crossing solid lane marking to carry out a lane change	2.87	1.12	1.55	0.77	**1.32**	1**
2. Turning the indication light when driving off or changing a lane	1.73	0.87	1.18	0.43	0.55	1**
3. Checking the side mirror and looking over shoulder before changing lanes	2.18	1.13	1.33	0.63	0.85	1**
4. Suddenly crossing a solid line to make a lane change	2.54	1.16	1.69	0.89	0.85	1**
5. Remaining on a lane with high speed even when this lane will end soon, finally making a forced lane changing	2.27	1.06	2.10	1.05	0.17	0
6. Losing patience to wait for a sufficient gap and make a forced lane changing in congestion	1.96	0.92	1.54	0.74	0.42	1**
7. Yielding for the driver whose lane will be end/closed	2.74	1.06	1.98	0.78	0.76	1**
8. Yielding for other drivers forced lane changing in congestion	3.58	0.97	2.45	0.87	**1.13**	1**
Overtaking						
1. Conducting overtaking even if the preceding vehicle already has the left indication on	1.47	0.76	1.49	**0.79**	**-0.02**	0
2. Overtaking from the right side if no chance on the left side	2.71	1.15	2.06	1.10	0.65	1**
3. Underestimating the speed of the oncoming vehicle during overtaking	2.03	0.96	1.84	0.89	0.19	1*
4. Checking whether being overtaken by another vehicle before conducting an overtaking	2.04	1.24	2.00	0.69	0.04	0
Others						
1. Illegally using mobile phone during driving	3.24	1.34	1.78	0.96	**1.46**	1**
2. chasing other driver's when being irritated	2.39	1.19	1.24	0.52	**1.15**	1**
3. Driving in a wrong lane	2.96	0.98	1.97	0.95	0.99	1**
4. Ignoring the speed limitation in urban areas	2.12	0.95	2.51	**1.07**	**-0.39**	1**
5. Often checking the mirrors when going straight on	1.45	0.73	1.86	0.55	**-0.41**	1**
6. Keeping driving on the left-most lane for long time	3.04	1.25	1.73	0.81	**1.31**	1**
Total	69.96	13.24	56.06	8.59	13.90	1**

** $p < 0.01$, * $p < 0.05$

Because every item in Table 5.2 is an ordinal variable, Mann-Whitney U test was used to study whether there were significant differences between Chinese and Dutch answers. Mann-Whitney U test is to verify the null hypotheses: *There is no difference in the answers between the answers of Dutch respondents and Chinese respondents*.

h = 1 indicates a rejection of the null hypothesis at the 5% significance level, i.e. indicating the significant difference between two countries.

h = 0 indicates a failure to reject the null hypothesis at the 5% significance level, i.e. no significant difference between two countries.

Mann-Whitney U test results are presented in Table 5.2.

Cronbach alpha reliability coefficients are often used to examine the internal consistency of the DBQ items (Davey *et al*., 2007; Fernandes *et al*., 2010). Because Cronbach's alpha is usually expected to increase with the inclusion of more items (Davey *et al*., 2007), 30 items related to driving behaviors are classified into 6 categories: Priority rules, Reaction to signal, Car following, Lane changing, Overtaking, and others. The aggressive scores were summed for every sub kind of driver behavior. The Cronbach's alpha reliability coefficients of DBQ scale scores are shown in Table 5.3.

Table 5.3 DBQ scales Cronbach's alpha reliability coefficients

Variable	**Number of variable**	**Cronbach's Alpha**	
		CN (215)	**NL (176)**
Behavior Category	6	0.790	0.692

Reliability analyses for the DBQ reveal that the alpha reliabilities for six categories typical behaviors were 0.790 in the Chinese sample, and 0.692 in the Dutch sample respectively. The values of Cronbach alpha indicate that Dutch data sample is less consistent than the Chinese one, while the internal consistency is still not low.

5.4.2 Driving behavior comparison

For most items (25 from 30), Chinese respondents got a higher aggressive score than the Dutch counterparts. It indicates that Chinese respondents were more aggressive in driving. Chinese respondents' average total aggressive score and the standard deviation were both higher than those of the Dutch respondents: 69.96±13.24 vs. 56.06±8.59. In Figure 5.1, a normal distribution is used to fit the data. It is clear that Chinese data have a higher average aggressive score with a large variation.

There were only two items for which Chinese respondents got much lower scores than the Dutch counterparts. The first one was the reaction to the yellow light. The possible reason is a new traffic rule decreed at the beginning of 2013 in China. Based on this rule, the penalty for crossing the stop line during the yellow phase is the same as crossing during the red phase. Even though this rule only lasted for six days and then was canceled, lots of respondents still did not know about the appropriate actions during a yellow phase and just gave the simple answers: brake to stop. The other item for which the Chinese data got a low aggressive score was the attitude to a big truck. This can be explained by the fact that the performance of trucks in China is worse compared with that in the Western countries. Thus Chinese drivers are quite careful with trucks in driving.

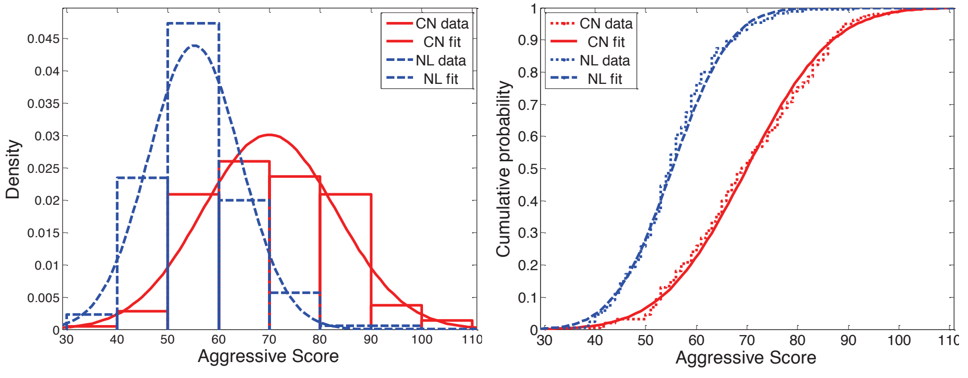


Figure 5.1 Aggressive score distribution (Left) and cumulative probability (Right)

Mann-Whitney U test shows the considerable difference in almost every DBQ item between Chinese and Dutch respondents. Chinese respondents were similar to the Dutch counterparts only in the following four items:

- Crossing the stop-line during the red phase
- Following a slowly moving vehicle
- Remaining on a lane with high speed and finally making a forced lane change
- Checking whether being overtaken by another vehicle before starting overtaking

Chinese respondents especially differed from the Dutch counterparts in the following seven items:

- Searching priority signs
- Reaction to the yellow light
- Crossing solid lane markings
- Cooperation in lane changing in congestion
- Using mobile phone
- Reaction to other driver's abnormal driving
- Keeping driving on the left-most lane

Table 5.2 illustrates a remarkable difference in self-reported driver behavior between China and the Netherlands. According to the aggressive scores measured from the answers to the questions, Chinese respondents were more aggressive than Dutch counterparts. The standard deviations in Chinese answers were much higher than the Dutch ones, which indicated a much larger variation of driver behavior in reality.

5.4.3 Priority rule implementation analysis

Priority rules are very important in traffic management. The implementation of priority rules can also be considered as a critical aspect in driving behavior. The aggressive score is expected to be strongly related to the attitude to priority rules in driving. Four questions concerning priority rules are involved in this questionnaire.

1. Priority signs recognition

In the questionnaire, several pictures related to priority signs were presented to respondents. These signs denote the drivers should give priority to the conflict traffic by an obligatory full stop or deceleration. The priority signs are marked on the road pavement or positioned on the road side. The respondents were asked if they know or ever saw these signs. The results are shown in Table 5.4.

Table 5.4 Survey of priority sign recognition

	Chinese Priority Signs			**Dutch Priority Signs**		
						
Unknown (%)	20.93	16.74	34.42	3.43	0.57	2.86
Unseen (%)	4.19	3.72	33.02	1.14	1.71	2.29
Known (%)	74.88	79.53	32.56	95.43	97.71	94.86

An extreme difference is found in the priority sign recognition between Chinese respondents and Dutch counterparts. As shown in Table 5.4, 33.02% of Chinese respondents indicated that they had never seen the priority sign on the road pavement, but this percentage is only about 4 for the two priority signs besides the road. The percentage of respondents who expressed they knew the priority sign is about 75 for road side signs and only 32 for the pavement sign. This reflects the fact that a quite large proportion of Chinese drivers can't recognize the priority signs; especially they don't have the habit to search traffic signs on the road pavement. In the Dutch DBQ results, more than 95% of respondents indicated they knew the priority signs besides the road or on the road pavement, and very few respondents expressed they had never seen or did not know the priority signs. The high proportion of priority signs recognition in the Netherlands can be ascribed to the fact that these signs are more ubiquitous in the Netherlands compared with in China. Do these drivers who gave the answer 'known' really fully understand the meaning of the priority sign? Another investigation introduced in Chapter 7 will reveal the truth.

2. Priority giving

There are two questions relevant to the implementation of priority rules in the questionnaire. The first one is 'In which case will you not give priority to pedestrians when you are turning right and sharing the green phase with the pedestrians?' The answers in percentage are shown in Table 5.5.

Table 5.5 Investigation on 'refuse to give priority to pedestrians'

Options	CN (%)	NL (%)
Never happen because I always give priority to pedestrians	42.39	84.57
Pedestrians never have priority	3.29	0.57
Congested traffic situation	13.99	3.43
When I am in a hurry	23.87	2.29
Too many pedestrian and too long time waiting make me lose patience	13.58	2.29
Others	2.88	6.86

According to Table 5.5, most Dutch respondents (84.57%) indicated they always gave priority to pedestrians; however this percentage in Chinese data was only 42.39. Among Chinese respondents, the most frequently selected reason for 'refuse to give priority to pedestrians' was 'When I am in a hurry' (23.87%), then was 'Congested traffic situation' (13.99%) and 'Too many pedestrian' (13.58%). For these three reasons, Dutch respondents only referred with much low percentages: 2.29, 3.43 and 6.86 respectively. These answers indicate that the driving behavior can vary to a certain extent under the influence of driver personal factors in China.

The other question concerning priority rules is 'If you see conflicting vehicles still staying at the signalized intersection while your signal is turning to green, what are your usual reactions?' The answers from two countries are shown in Table 5.6.

Table 5.6 Investigating on the reaction to conflicting vehicles

Options	CN (%)	NL (%)
Still driving, because it is my green time	5.81	5.14
Giving priority to the conflicting vehicles because they are from the previous phase	37.76	53.14
Depend on the traffic situation: in congestion, if other people squeeze me, I will also squeeze the conflicting vehicles	32.37	20.00
Depend on my situation: hurry then squeeze the conflicting vehicles	21.16	6.86
Others	2.90	14.86

For the scenario described in this question, Dutch respondents still had a higher probability to give priority to the conflicting vehicle than Chinese respondents: 53.14% vs. 37.76%. The most frequently mentioned reason for not giving priority to conflicting vehicles is congested traffic situation (32.37% in Chinese data and 20% in Dutch data). Besides, 21.16% of Chinese respondents selected 'depend on my situation' and this value was only 6.86% in Dutch Data. This survey results prove that the traffic conditions can influence driving behavior remarkably in both two countries.

5.5 Factor Analysis

The results of the comparison presented in the previous sections 5.3 reveal a marked difference in self-reported driver behavior between China and the Netherlands. It is important to explore what factors can result in such discrepancy. In this section, the analysis will be made through two methods: factor analysis and nonparametric test.

5.5.1 Factor analysis

In statistical analysis, factor analysis is often used to identify underlying factors that can explain the correlations within a set of observed variables. Lots of DBQ studies introduced in the literature used factor analysis to investigate the applicability of the DBQ in different countries (af Wåhlberg *et al*., 2011; Davey *et al*., 2007; de Winter and Dodou, 2010; Lajunen *et al*., 2004; Wishart *et al*., 2006). In this study, factor analysis was used to identify the correlations among the items in the questionnaire, especially the relationship with the aggressive score. The variables in the factor analysis should be quantitative at the interval or ratio level, so gender and occupation, as categorical data, should not be included in the factor analysis. The sum of aggressive scores can be considered as the integrated indication of driving style. Totally, DBQ score and 12 items related to demographic information (e.g. gender, age, etc.) and basic driving information (driving experience, accidents, etc.) are involved in the factor analysis, as shown in Table 5.7.

In factor analysis, Scree plots together with Eigenvalue of each component (SPSS 17.0, 2007) are often used to determine the optimal number of components. The scree plots are drawn for Chinese data and Dutch date respectively, as shown in Figure 5.2. The optimal number of component should be at the turning point of the Scree plots and the Eigenvalue should be larger than 1. According to Figure 5.2, the optimal number of component was finally determined as four. The percentage of variance explained by the first four components was 60.207 and 59.957 in Chinese data and Dutch data respectively, as shown in Table 5.7.

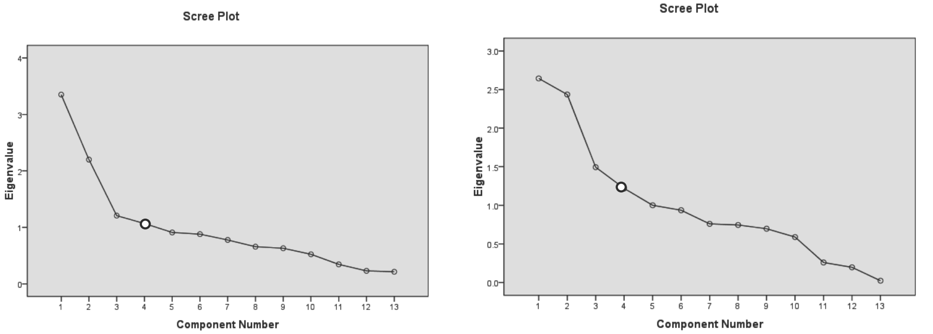


Figure 5.2 Eigenvalue Scree Plot for Chinese data (left) and Dutch data (Right)

Table 5.7 shows some underlying relationships between the variables in the four-factor component structures in two countries' data. The component structure is quite consistent in the first three factors between the investigated two countries. In both two countries, Factor 1 involves three variables (age, driving experience in year, and yearly driving mileage) which can be classified as '*driving experience*'. The difference is that Chinese Factor 1 also contains self-estimated driving skill and Dutch Factor 1 includes driving frequency and offences recording. Items related to '*driving exposure*', like driving frequency, yearly mileage, offence and accident, are included in Factor 2 in Chinese; and most of these items, except accident, are included in Factor 3 in the Dutch data. Three items directly related to '*driving style*' (Self/others estimated driving style, Aggressive Score) are involved in Factor 2 in Dutch data. Factor 3 of Chinese data comprised the items related to driving style. These two data-sets are quite different in the Factor 4. Three items (enjoy driving, skill and experience) are included in the China data; whereas the other three items (education, frequency and accident) are involved in Dutch data respectively.

Table 5.7 Four-factor rotated component matrix of the Chinese data and Dutch data

	Factor 1		Factor 2		Factor 3		Factor 4	
	CN	NL	CN	NL	CN	NL	CN	NL
Experience	0.822	0.900					0.305	
Age	0.747	0.902						
Education	0.622							-0.665
Offence		0.317	0.715			0.481		
Frequency		0.488	0.689			0.539		0.368
Ownership			0.611			0.606		
Mileage	0.489	0.688	0.597			0.446		
Self-estimated driving style				0.906	0.915			
Others estimated driving style				0.890	0.896			
Accident			0.373		0.428			0.753
Enjoy Driving						0.520	0.771	
Skill	0.352		0.300			0.568	0.682	
Aggressive Score				0.442	0.388			
Cumulative Variance (%)	16.000	19.814	31.930	34.922	47.832	49.602	60.207	59.957

Note: The factors with absolute values of factor loading below 0.30 were omitted for the sake of clarity.

An important conclusion can be made from the factor analysis: *Aggressive score is correlated with self/others estimated driving style in both two countries*. Driving style is independent of most demographic factors. When comparing aggressive scores in DBQ obtained by the respondents from two countries, another interesting conclusion can be drawn: *the Chinese drivers underestimate their aggressiveness in driving*. The self-estimated aggressiveness made by Chinese respondents is consistently lower than that made by Dutch respondents. However, they got much higher aggressive scores in DBQ. Thus, Chinese respondents did not yet know that they were much more aggressive than what they self-estimated.

5.5.2 Nonparametric test

Gender and occupation are categorical variables whose correlation with aggressive score can be analyzed through nonparametric tests. In this study, Mann-Whitney U test was used to determine whether the aggressive scores vary between male and female drivers. The influence of respondents' occupation on their aggressive score is evaluated by Kruskal Wallis Test. These two tests are both based on the null hypotheses:

Independent samples classified by gender or occupation come from the same population.

If the significance *p*-values are smaller than 0.05, the null hypotheses will be rejected and indications for a significant difference exist. Otherwise, no significant difference can be determined and the correlation between the tested variables is quite weak. The significance *p*-values of tests are displayed in Table 5.8.

Table 5.8 *p*-values of nonparametric independence test

	Test	CN	NL
Gender	Mann-Whitney U	0.083	0.044
Occupation	Kruskal Wallis Test	0.333	0.031

According to the test results shown in Table 5.8, gender and occupation both have effect on driving behavior of Dutch respondents, with *p*-values of 0.044 and 0.031 respectively. However, the relation of the aggressive score to gender and occupation are both insignificant in the Chinese data, because of the *p*-values 0.083 and 0.333 respectively. Therefore, the high proportion of male respondents in Chinese data sample cannot account for the high DBQ aggressive score obtained by Chinese respondents.

5.6 Discussion and Conclusions

An online DBQ survey was carried out in China and the Netherlands at the same time based on the research questions presented in Section 5.1. The design of the questionnaire, survey procedure, and DBQ analysis results are introduced in this Chapter. Several research objectives have been achieved:

- *Revealing the remarkable differences in self-reported driver behavior between China and the Netherlands;*

Chinese respondents reported much more offences and accidents than the Dutch counterparts. Mann-Whitney U tests show the considerable difference in most DBQ items (26 out of 30) between China and the Netherlands.

- *Developing an indication, the DBQ aggressive score, to represent driver behavior;*

The aggressive score is introduced to evaluate driving style in terms of the answers on 30 items related to driver behavior. Chinese respondents got higher scores and also have remarkably larger variations on most DBQ items than Dutch respondents. These can be considered as the evidence of aggressive and heterogeneous driving behavior of Chinese drivers.

- *Identifying the factors that can influence driver behavior significantly;*

Factor analysis indicates that aggressive score is correlated with self/others estimated driving style in both two countries. That indicates that most respondents in the survey can evaluate their own driving style well, in comparison with other local drivers. The low self-estimated aggressiveness and the high aggressive score in DBQ reveal that Chinese respondents underestimate their aggressive driving style. Nonparametric tests indicate that gender and occupation both have effect on driving behavior of Dutch respondents, but no significant relation with the driving style of Chinese respondents.

- *Exploring some measures to improve driver behavior in practice.*

The survey on the implementation of priority rules reveals an extreme difference between two countries. A large percentage of Chinese respondents do not fully understand the priority rules in driving and don't have the habit to search traffic signs in reality. Chinese respondents offered much less priority to the conflicting pedestrians and vehicles than the Dutch counterparts in the same scenarios. Based on these survey results, it is proposed that the driving training and testing system in China should pay sufficient attention to the study of traffic rules and the enforcement in reality. The installation (or marking) of traffic signs should be standardized and be easily recognizable.

The DBQ survey carried out in China and The Netherland reveals that Chinese drivers have higher aggressive scores, large variations in driver behavior, more registered traffic rule offences and more accidents involved. This conclusion is consistent with the findings (aberrant driver behavior, heterogeneous traffic flow) made in Chapter 4. It is also revealed that most Chinese drivers are not clear with the priority rules. As a result, Chinese drivers are always uncertain and hesitant while driving, which makes the traffic flows inefficient.

The significant differences in self-reported driving behavior and the observed difference in traffic performance in Chinese cities show that capacity manuals and design standards have to be adapted to Chinese conditions. Simulation programs have to be calibrated based on Chinese driver behavior, especially the behavior at intersections and the behavior of lane changing.

The results of this DBQ survey support such conclusions that external factors (e.g., the enforcement of traffic rules, and traffic situation) are as important as the internal factors (e.g., driving attitude, driver's mood) to driving behavior in practice. This study is solely based on self reported behavior and no observation data are involved in this Chapter. Even though DBQ studies have been proved as an effective method to study driving behavior in the literature, it is still possible that some respondents gave some socially desirable answers. Therefore, in-car tests to collect the data related to driving in reality have been carried out and the detailed results are presented in Chapter 6. After that, a series of focus group sessions were organized to reveal drivers' opinions and thinking process in driving in China. More details can be found in Chapter 7.

Chapter 6

Driver Behavior In-car Test

6.1 Introduction

Driver behavior is not only considered to be closely related to traffic safety (af Wåhlberg *et al*., 2011; Bonsall *et al*., 2005; Emmerson, 2008; Kircher and Andersson, 2013; Nordfjaern *et al*., 2011), but also critical to traffic capacity (Lam, 1994; Li *et al*., 2012; Rahman *et al*., 2005).The Driver Behavior Questionnaire (DBQ) is a well-documented instrument for collecting self-reported information of driving behavior (af Wåhlberg *et al*., 2011; Bener *et al*., 2008; Davey *et al*., 2007; Lajunen *et al*., 2004; Martinussen *et al*., 2013). Chapter 5 introduces a DBQ survey conducted both in China and the Netherlands. The analysis reveals the remarkable differences in driver behavior between these two countries. According to the DBQ survey results, most Chinese respondents under estimated their aggressiveness in driving, and have many recorded offences and a high probability of accident involvement. Besides the rather higher aggressive scores in most DBQ items, Chinese respondents' driving behavior appears to be heterogeneous, varying from slow and cautious to aggressive driving. However, there is only limited information showing the relation between DBQ aggressive scores and actual driver behavior. This chapter aims to verify the DBQ aggressive scores by comparing them with driving behavior observed in reality.

In the literature, even though plenty of research is related to DBQ, the main research subjects are either the prediction of crash involvements, or the relation between traffic accidents and a variety of demographic characteristics, such as age, gender, occupancy, etc. (af Wåhlberg *et al*., 2011; Moller and Gregersen, 2008; Reason *et al*., 1990). There are a few studies that focus on the relationship between the answers in DBQ or interviews and the driving behavior in reality. Kondyli and Elefteriadou (2009) organized focus group discussions to collect knowledge about drivers' thinking process when they are merging to a freeway. After that, they developed a turbulence model for merging behavior and the evaluated this model through in-vehicle experiments on the road (Kondyli and Elefteriadou, 2011). Sun and Elefteriadou (2010) conducted another focus group study to get an insight into the lane-changing behavior on urban roads. A proposed lane-changing model was implemented in microscopic simulation program CORSIM and compared with the original model by using the traffic data collected in a busy arterial street. Both these two studies have developed a new model with data collected from the focus group discussions or in-car tests without focusing on the data validation. Stephens and Groeger (2009) analyzed the correlation between DBQ scores and driving behavior in a simulator, but this test still did not use the data collected from the field observation. Zhao *et al*. (2012) found that drivers with higher offences scores drive faster, have poorer lateral control, change lanes more frequently, spent more time on the left lane, and had more sudden unidirectional accelerations. This study only focused on the relationship between DBQ scores and observed highway driving behaviors. Perez-Zuriaga *et al*. (2013) combined GPS data and DBQ data to obtain the individual speed profile along the observed road segments for each driver and then developed and calibrated a speed profile prediction model. This study mainly addressed the conformance of highway geometry to actual driving speeds on two-lane rural roads. Therefore, very limited studies combined the DBQ answers (or interview answers) and the data related to acutal driving.

This study focuses on Chinese driver behavior on urban roads. The majority of questions in DBQ are relevant to this research subject. Several reasons can be found to query the validity of the conclusions drawn from the DBQ survey. A slight deviation in understanding the DBQ questions by the respondents may result in a quite large discrepancy in answers. In addition, respondents of DBQ are also possibly inclined to give socially desired answers and conceal their real driving behavior. Therefore, it is necessary to investigate Chinese driver behavior in reality, and then to compare the analysis results with the DBQ conclusions. In-car tests in urban traffic situations can provide more details of actual driving behavior, and is expected to achieve the following research objectives:

- To validate the conclusions drawn from the DBQ survey;
- To check whether the filling in of a DBQ has influence on actual driving behavior afterwards;
- To explore the relation between the DBQ scores and driver behavior on urban roads;
- To collect specific data from field observations of driving;
- To carry out a further analysis on driving characteristics;
- To establish a solid foundation for the calibration of simulation programs, like VISSIM.

Thirty Chinese volunteers balanced by gender, age and occupancy were invited to take an in-car test. Eighteen participants completed a DBQ before the tests, and the other twelve participants filled in the same DBQ after the tests. Details of DBQ can be found in Chapter 5 and Appendix C. Section 6.2 introduces the general information about the participants, the test method and the procedure. In section 6.3, the acceleration and deceleration behavior characteristics will be revealed. The investigation results regarding lane changing behavior will be presented in Section 6.4. Subsequently, a comparison between DBQ answers and actual driver behavior is made in section 6.5. Some important conclusions and recommendations for the future study are presented in section 6.6.

6.2 Methodology

This section describes the data collection methodology on urban roads in Changsha city, China. Data collected by in-car tests include: driving paths, speed and acceleration profiles, demographic information, and vehicle type of every participant, etc.

6.2.1 Participants

Most participants were volunteers recruited in Changsha (China) and did not receive any reward for taking part in the study, except four taxi drivers who were paid according to the taxi fee rate in Changsha. Participants' driving experience varies from half a year to thirty four years, including six professional drivers. Participants were asked to fill in a DBQ before the in-car tests or after the in-car tests. Table 6.1 shows the summary of basic demographic information and DBQ aggressive scores. More details about the DBQ results can be found in Chapter 5 and the specific items of DBQ are presented in Appendix C.

Table 6.1 Characteristics of the Chinese DBQ sample and in-car test sample

Item	**DBQ sample (*n* =215)**	**In-car test (*n*=30)**	**Note**
Mean age (SD)	36.01 (8.05)	39.9 (6.15)	
Males (%)	80.0	73.3	
Professional driver (%)	4.65	20.00	
Mean driving experience in years (SD)	6.19 (6.33)	8.40 (7.99)	
Enjoy driving (SD)	6.92 (2.14)	7.17 (2.32)	1= dislike; 10 = enjoy very much
Self-estimated driving type (SD)	3.95 (2.08)	4.47 (2.37)	1 = very conservative; 10 = very aggressive
Others-estimated driving type (SD)	4.25 (2.14)	4.73 (2.42)	1 = very conservative; 10 = very aggressive
Self-estimated driving skill	6.44 (2.15)	7.00 (2.05)	1 = very poor; 10 = very excellent
Offences recording last year (%)	57.7	70.0	
Accidents involved in previous 5 years (%)	51.2	70.0	
DBQW Aggressive score	69.96 (13.24)	69.93 (14.59)	

Even though the in-car test sample is not randomly selected from the Chinese DBQ sample, most of the characteristics of these two data samples are similar to each other. The Mann-Whitney U test is used to determine whether there is a significant difference in aggressive scores between Chinese DBQ sample and in-car test sample based on the null hypotheses: *There is no difference in the aggressive scores between the two data samples*. The test result indicates the significance p-values of test is 0.632 (larger than 0.05) and the null hypotheses cannot be rejected. Therefore, there is no significant reason indicating a difference exists in aggressive scores in the two driver samples.

6.2.2 Apparatus

In-car tests were conducted in participants' own vehicle, passenger car or SUV, that was instrumented GPS devices and three video cameras. In this study, two kinds of GPS devices were used: one is a normal GPS device and the other is DGPS (Differential GPS). Both two GPS devices recorded vehicles' positions and speed at 1 Hz. The only difference of these two GPS data sources was in the position precision. In this chapter, data from the normal GPS device with the distance accuracy at meter level was used to deduce the acceleration profile for every participant (Li *et al*., 2011c). Coordinate data recorded by DGPS are very precise, achieving centimeter level. Because there was only one GPS base station was connected with the DGPS device during the tests, driving trajectories drawn from DGPS are not complete and consecutive. Therefore, DGPS data were only used to calibrate lane changing models in the further study.

During the driving tests, the GPS antenna was fixed on the top of the vehicles, transferring data to a GPS device and a laptop through a wire. Three video cameras were installed to record the traffic situation in front, the face of the driver, and the manual operation of the driver respectively. The installation of the GPS device and three cameras are demonstrated in Figure 6.1.

Figure 6.1 Equipment layout in a testing vehicle

The information about the test vehicles is summarized in Table 6.2. Most test vehicles are passenger cars, automatic gears, and not old (with a mean age 3.02 year). Vehicles' mean driving mileage is not long (79,270 km), but with a quite large standard deviation (96,320 km).

Table 6.2 Characteristics of the test vehicles

Item	**Testing sample (*n* =30)**
Vehicle type	Passenger car 70%, SUV 20%, Taxi 10%
Gear type	Automatic 73.33%, Manual 26.67%
Vehicle age (year)	3.02 (SD 1.79)
Driving mileage (1000km)	79.27 (SD 96.32)
Average testing time (min)	29.53 (SD 8.49)

In summary, the GPS device collected the following data related to the test vehicles at the frequency of 1Hz:

- Instantaneous position;
- Instantaneous speed;
- Acceleration/Deceleration calculated from speed.

These microscopic data will be used to study the drivers' acceleration/deceleration characteristics.

The video observation recorded the following data and information:

- Lane changing data: times, objectives and related behavior (see Section 6.4);
- Lane using: time distribution on different lanes;
- Aberrant driving behavior: crossing solid lines to change lanes, mobile phone using, overtaking on the right side, etc. (see Section 6.5).

These data are expected to verify the answers in DBQ and to develop the relation between actual driving behavior and DBQ scores.

6.2.3 Procedure

The in-car tests were conducted on the urban roads in Changsha city with which the participants were familiar. The driving routes included arterial roads, minor roads, and a few high speed ring-roads. The arterial roads in Changsha usually comprise 4 or 6 lanes in two directions; with almost all intersections signal controlled and a speed limit of 60 km/h. Minor roads often consist of 2 or 4 lanes with most intersections signalized, but usually without speed limit signs. High speed ring roads in Changsha have a speed limit of 80km/h and 4 lanes in two directions, without any at-grade crossings. To guarantee the safety of the test, participants were asked to drive in a car with which they often drove.

At the beginning of the test trip, participants were told to select a lane to drive on or to overtake other vehicles according to their own driving behavior. In order to exclude the influence of external factors (weather, light, traffic volume density, etc) on driver behavior, all in-car tests were conducted at off-peak hours, during day time and under good weather conditions. Thirty drivers completed thirty six trips from May to June, 2013. The total testing time was 1063 minutes; every trip lasted for about half an hour without any traffic incidents occurring. Five drivers took the tests more than once. Thus, the reliability of driver behavior was expected to be studied by these duplicated tests.

6.3 Acceleration and Deceleration Behavior Analysis

Driving under a certain traffic condition, a driver needs to adjust his/her driving speed by accelerating or decelerating. Therefore, acceleration or deceleration characteristics are an important feature of driver behavior. This section addresses the acceleration and deceleration behavior analysis and the correlation with DBQ scores.

6.3.1 Data preparation

The research presented in this dissertation not only focuses on Chinese driver behavior, but also on the micro simulation model calibration which requires the data collected at microscopic level. The GPS devices can record instantaneous speed and acceleration/deceleration of every test trip at the frequency of 1Hz. These data are used for the model calibration, as introduced in Chapter 8.

Speed classification

During the in-car tests, the GPS device recorded the synchronous information of coordinate, speed, and acceleration of the test vehicles. In actual driving, the acceleration is correlated with the speed. For example, combustion engines reach their maximum acceleration at a low speed and the acceleration decreases with the speed increasing. On the contrary, the deceleration is large at a high speed and falls with the speed decreasing. To study the drivers' acceleration characteristics, the acceleration should be analyzed for different speed classes. For every test trip, the speeds were classified into 8 classes: 2~5km/h, 5~15km/h, 15~25km/h, 25~35km/h, 35~45km/h, 45~55km/h, 55~65km/h, >65km/h. The moments with a low speed (lower than 2km/h) lasting for more than 2 seconds were considered as a stop of the vehicle. The number of stops per hour can be considered as an indicator of the traffic situation and was counted for every test trip. Very low speeds (≤ 0.1km/h) were excluded due to the noise of the GPS data.

Acceleration/Deceleration profiles

To represent the stochastic property of driver behavior in reality, acceleration and deceleration are often described as functions of the current speed rather than a single acceleration and deceleration value in some simulation models. For example in VISSIM, each vehicle type has two acceleration/ deceleration characteristics: maximum acceleration/deceleration and desired acceleration/ deceleration. Maximum acceleration/deceleration is a kind of technical property and is rarely used in reality. Desired acceleration/deceleration reflects the driver's desire to achieve the ideal speed or to adapt to the current traffic surroundings (PTV, 2013). In this study, the average values of acceleration/deceleration and standard deviations were calculated for 8 speed classes for every trip.

Due to the numerical characteristic of the GPS device, standstill vehicles were often recorded with speed zero or 0.1km/h. Therefore, instantaneous acceleration was identified as two consecutive speeds both larger than 0.1 km/h and the difference in speed were divided by one second. In order to filter the data outliers of every trip, acceleration/deceleration data only between 5 percentile and 95 percentile were reserved for the profiles analysis.

Density calculation

Traffic density is considered as an important external factor influencing driver behavior in reality (Dijker *et al*., 1998; Zhang and Mahlawat, 2008). The driving speed is determined by the traffic density, and has an impact on the acceleration and deceleration in practice. Therefore, traffic density should also be correlated with acceleration and deceleration profiles, as demonstrated in Figure 6.2. The analysis of the relation between the acceleration/deceleration characteristics and the prevailing traffic condition is another purpose of this study. It is expected to explore some significant information for micro simulation model calibration and modification.

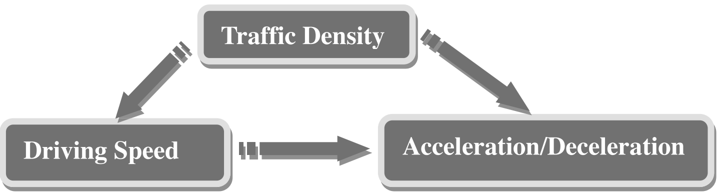


Figure 6.2 Interrelationship among traffic density, speed and acceleration/deceleration

With the limited traffic information, traffic density k can be approximately deduced from the relation between the instantaneous mean speed v and the traffic flow q according to the fundamental diagram (Daganzo, 1997), as shown in Figure 6.3.

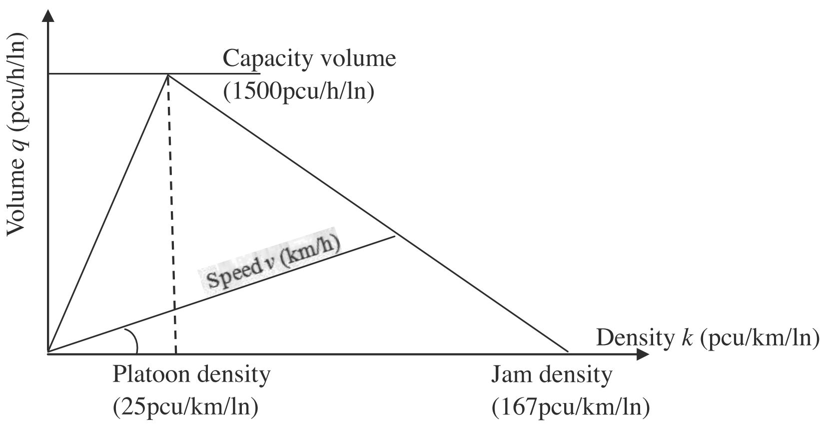


Figure 6.3 Simplified fundamental diagram for one lane

According to the study results presented in Chapter 4, the platoon capacity flow rate is 1500 pcu/h/ln in Changsha City. The speed limit of arterial roads is 60km/h which is supposed to be the free speed. For Changsha traffic, the free speed and capacity together determine the platoon density 25pcu/km/ln. Jam density is measured as 167 pcu/km/ln. As shown in the fundamental diagram Figure 6.3, the traffic volume q is the function of traffic density k:

When $k < 25$ veh/km/lane, $q = 60\ k$

When $25 \le k < 167$ veh/km/lane, $q = 1764 - 10.56k$
When $k \ge 167$ veh/km/lane, $q = 0$
Thus,
when $0 < v \le 60$ km/h $k = 1764/(v+10.56)$ (6.1)
when $v > 60$ km/h $k = 1500/v$

Based on Functions (6.1), the traffic density k at different instantaneous median speed v can be estimated, as shown in Table 6.3.

Table 6.3 Traffic density calculation

Speed Scope (km/h)	Median speed (km/h)	Density (pcu/km/ln)
<2	0	stop
2~5	3.5	125
5~15	10	86
15~25	20	58
25~35	30	43
35~45	40	35
45~55	50	29
55~65	60	25

The average density for every trip is calculated as:
$\text{Density} = \text{Density}_{speed\_1} * \text{Time\_Percentage}_{speed\_1} + \text{Density}_{speed\_2} * \text{Time\_Percentage}_{speed\_2} + \ldots$

6.3.2 Factor analysis

As presented in Chapter 3, driver behavior has been proved to be related to impersonal properties, e.g. traffic situation, and personal properties, e.g. gender, in terms of previous studies. In this study, the correlation between acceleration/deceleration characteristics and other factors is explored by two methods: factor analysis and nonparametric tests. Factor analysis is suitable for the ordinal and scale variables, rather than nominal variables, like gender. Nonparametric tests are more applicable for nominal variables.

Factor analysis originated in psychometrics is appropriate to deal with large quantities of data in lots of fields, such as behavioral sciences, social sciences, marketing, product management, and operations research (Bartholomew *et al*., 2008). At present, factor analysis is an often used statistical method to reveal the interdependencies between observed variables. The gained information about the interdependencies can be used to reduce the set of observed variables into a lower number of unobserved joint variables called factors which cover the variation in the full data set for a great deal. Additionally, factor analysis can also be used to generate hypotheses regarding causal mechanisms or to identify variables for subsequent analysis (SPSS 17.0, 2007).

In this study, the factor analysis on acceleration/deceleration characteristics involves mean values and standard deviations of acceleration/deceleration for five speed classes, driving experience, DBQ aggressive score, and traffic density. Accelerations/decelerations at the speeds higher than 45km/h have been excluded due to the lack of such high speed of some trips. Variables related to speed (mean speed, speed standard deviation, the number of stops per hour) have been omitted from the factor analysis data-set, because they are basically the same characteristic with an intermediate transformation, as explained in Function (6.1) and Figure 6.2.

In factor analysis, the Eigenvalues of each factor are plotted in descending order, this plots are called scree plots. The large Eigenvalues and the turning point in the scree plots can be considered together to identify which factors should be retained (SPSS 17.0, 2007). As shown in Table 6.4 and Figure 6.4, the number of components of the in-car test data set can be determined as 4.

Component	Initial Eigenvalues
1	11.068
2	2.950
3	2.014
4	1.434
5	0.978

Table 6.4 Initial Eigenvalues

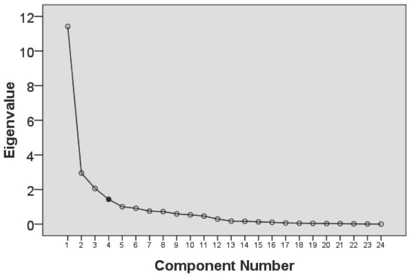


Figure 6.4 Eigenvalue Scree Plot

In order to simplify the interpretation of the factors, an orthogonal rotation method was applied to minimize the number of variables that had high loadings on each factor, as shown in Table 6.5. 75.9% of the variance of this dataset was explained by these four components. The close correlation between variables was also highlighted after rotating the component.

The loadings of traffic density in all four factors are all larger than 0.3, which implies that traffic density, representing the traffic situation, is an important variable correlated with most of the other variables. In the four-factor rotated component matrix, a variety of variables have loadings larger than 0.3 in every factor. However, more attention should be paid to the largest loading of every variable (the boldfaced numbers) to identify the underlying pattern of correlations.

Table 6.5 Four-factor rotated component loading matrix

Variable		Factor 1	Factor 2	Factor 3	Factor 4
DBQ Aggressive Score				**.404**	.387
Driving experience in year					**.645**
Traffic density		**-.503**	-.383	-.467	-.389
Mean acceleration at speed	0.1~5 km/h	.397		.327	**.630**
	5~15 km/h	**.631**	.552		.355
	15~25 km/h	.415	**.769**	.322	
	25~35 km/h		**.725**	.565	
	35~45 km/h		**.691**	.575	
Std acceleration at speed	0.1~5 km/h	.300			**.782**
	5~15 km/h	.446	**.656**		.391
	15~25 km/h		**.858**		
	25~35 km/h		**.791**	.440	
	35~45 km/h		**.696**	.541	
Mean deceleration at speed	0.1~5 km/h	**-.820**			-.372
	5~15 km/h	**-.787**	-.385		
	15~25 km/h	-.538	-.333	**-.590**	
	25~35 km/h			**-.824**	
	35~45 km/h		-.470	**-.516**	-.393
Std deceleration at speed	0.1~5 km/h	**.887**			
	5~15 km/h	**.857**	.335		
	15~25 km/h	**.718**		.454	
	25~35 km/h			**.868**	
	35~45 km/h			**.655**	.419
% of Variance		22.623	22.211	19.592	11.515

Note: 1. The factors with absolute values of factor loading below 0.30 were omitted for the sake of clarity.
2. The bold numbers indicate the largest loadings of variables in the component matrix.

Factor 1 is correlated with variables related to deceleration and acceleration at low speeds. However, deceleration at low speeds is a better representative for this Factor 1 than acceleration, because it's loading in Factor 1 is higher than in the other three factors. Variables related to acceleration play a critical role in Factor 2, except the acceleration at a very low speed. Factor 3 presents the importance of aggressive scores derived from the DBQ and deceleration at high speeds. For Factor 4, the most significant variables are driving experience and acceleration at very low speeds. This suggests that attention should be paid to deceleration, acceleration, DBQ aggressive score and driving experience in the further analyses. Through this factor analysis, the number of variables of every testing driver was reduced to four which could explain 75.9% of the driving characteristics.

6.3.3 Acceleration/Deceleration characteristic categorizing

Regression was used to estimate a factor score for every tested driver. The mean value of the scores was 0 and the variance equaled to the squared multiple-correlation between the estimated factor scores and the true factor values (SPSS 17.0, 2007). In the next step, the drivers were clustered into several relatively homogeneous groups based on their four factor scores. If every clustering group can represent a kind of typical driving behavior, one may expect that traffic simulation models can be calibrated based on the driver group characteristics and become more consistent with driver behavior in reality.

K-Means Clustering is a popular method used to partition the observations into *k* clusters so as to minimize the within-cluster sum of squares (WCSS) via an iterative refinement approach (Hartigan and Wong, 1979). In this study, four homogeneous driving types were clustered by K-Means Clustering method based on drivers' factor scores. After three iterations, convergence was achieved since no or small changes in cluster centers occurred in the last iteration. F-test was used to explore which factors contribute the most to the final cluster solution. The F-values for these four factors are 6.757, 5.531, 10.623 and 15.910 respectively, which indicates that Factor 3 and Factor 4, having high F-values, give a great separation between the clusters. Driving type 1 involved 10 test trips. Driving type 2 was the largest group which includes 16 test trips. Driving type 3 and Driving type 4 both contain 5 test trips.

Scatter plots of factor scores were drawn to reveal the characteristics of every driving type. The horizontal axes and vertical axes represent different factor scores, as show in Figure 6.5. For example, the first plot in the first row shows the Factor 1 score on the horizontal axis, versus the Factor 2 score on the vertical axis. The differences between Driving type 1 and Driving type 2 can be seen in the difference of their Factor 2, rather than Factor 1, because their scores for Factor 1 are still similar. Driving type 1 has high scores in Factor 2 and Factor 3. On the contrary, the scores of Driving type 2 are low in Factor 2 and Factor 3. The typical characteristics of Driving type 3 are high scores in Factor 1 and Factor 4. Driving type 4 has a quite low score in Factor 3, but high scores in Factor 2 and Factor 4. More details about the driving type description are presented in Table 6.6.

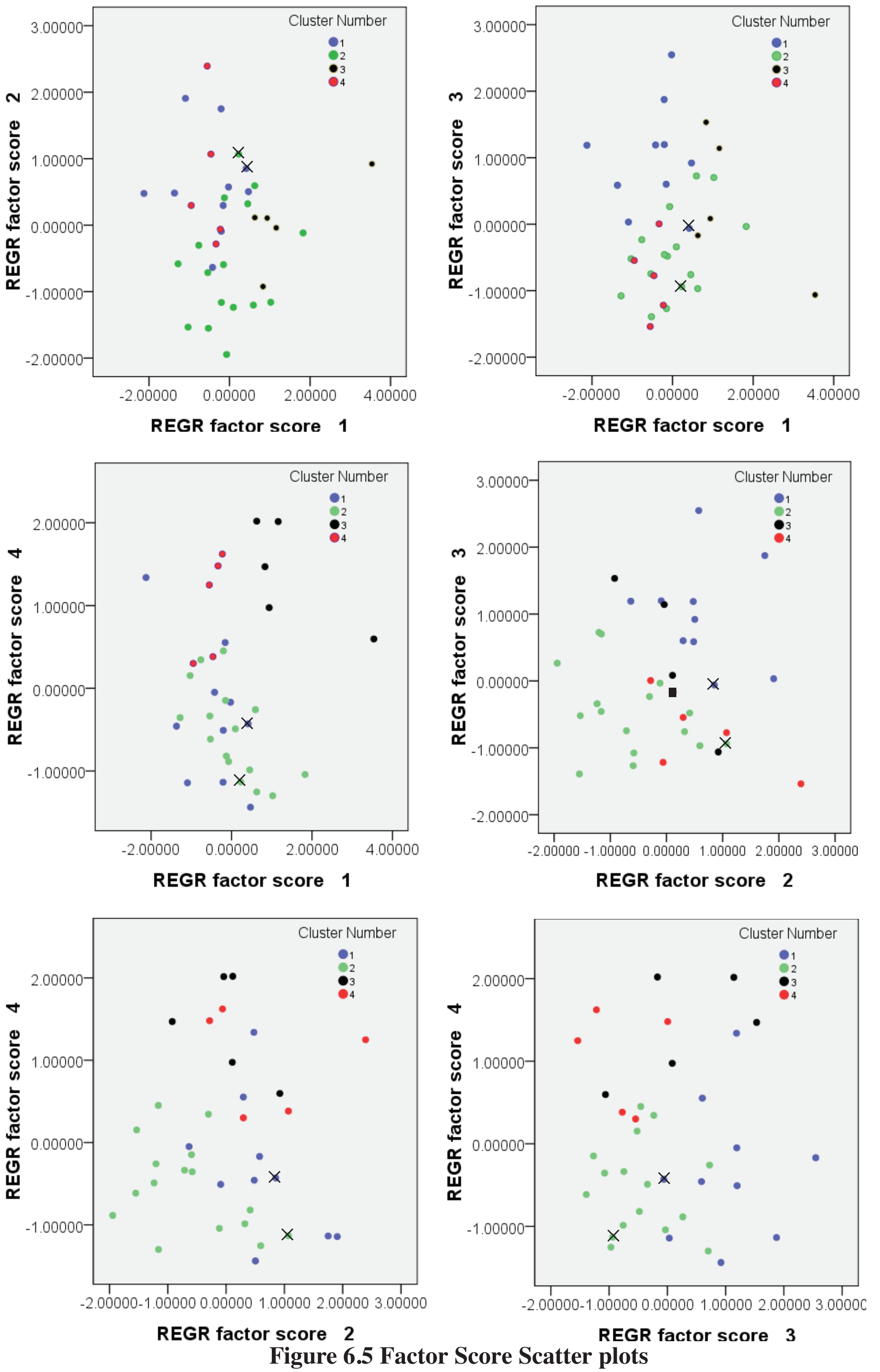


Figure 6.5 Factor Score Scatter plots

Note: '×' indicates two trips made by the same driver falling in different categories. More details will be explained in the next paragraph.

Table 6.6 Driving type category

Type	Number	Factor	Description	Type Name
1	10	High F2; High F3	High aggressive score, high acceleration and high deceleration at high speed, and more accidents	Aggressive, male, unsteady
2	16	Low F2; Low F3; Low F4	Low aggressive score, short driving experience, low acceleration at all kind of speed, low deceleration at high speed, and more accidents	Conservative, female, novice
3	5	High F1; High F4	Experienced, high acceleration and deceleration at low speed, more offences registered	Professional, smooth-going
4	5	High F2; Low F3; High F4	Experienced, low aggressive score, always high acceleration, but low deceleration at high speed, less recorded offences and less accidents	Experienced, speeding

The four driving types categorized in Table 6.6 will be used in the micro-simulation model calibration in Chapter 8.

As introduced in Section 6.2, thirty participants completed thirty six trips and five drivers took the in-car tests more than once. It is interesting to know whether the different trips made by the same driver would still belong to the same driving type. The stability of driver behavior, as well as the rationality of the driving type category method, is expected to be verified by these duplicated tests. Indeed, most of the different test trips made by the same drivers were still in the same driving type groups, except two trips of a female driver (See the '×' in Figure 6.5). This driver only had two years of driving experience when she was taking the in-car tests. The difference between these two trips was not in Factor 1 and Factor 2, but in Factor 3 and Factor 4. That means this driver's characteristics of acceleration at high speeds and deceleration at low speeds were stable, while the characteristics of acceleration at low speeds and deceleration at high speeds were sensitive to the traffic context.

Traffic density is relevant to driving acceleration and deceleration, as demonstrated in Figure 6.2. Why do different trips made by the same driver still have similar acceleration /deceleration characteristics? The plausible reason is that the traffic situations did not vary too much: all trips were made at an off-peak hour in an urban area. In Table 6.4, all the loadings of traffic density in every factor are not so high, which also implies the weak correlation of the traffic density with other variables. This result also indicates the stability of driving behavior, and supports the rationality of driving type classification. If the external traffic situation does not vary too much, driver behavior can remain consistent for a great deal. The acceleration/deceleration behavior classification method introduced in this section can limit the redundant observed variables and represent the main driver characteristics.

6.3.4 Nonparametric tests

The two-independent-sample tests are often used to compare two groups of cases with one variable. The correlation between acceleration/deceleration characteristic and nominal variables, like gender, vehicle type, driver occupancy, can be identified by the Mann-Whitney U test (a kind of two independent samples tests). The Mann-Whitney statistics is used to test the null hypothesis that two independent samples come from the same data sample; namely factors (gender, vehicle type, driver occupancy, in-car test before or after DBQ survey) do not influence acceleration/deceleration characteristics significantly.

h = 1 indicates a rejection of the null hypothesis at the 5% significance level, i.e. indicating the significant difference between two groups.

h = 0 indicates a failure to reject the null hypothesis at the 5% significance level, i.e. no significant difference between two groups.

The two-tailed significance values of Mann-Whitney U tests of acceleration/deceleration characteristic are presented in Table 6.7 and Table 6.8. The Mann-Whitney U tests for gender demonstrate that male and female drivers only differ in most acceleration characteristics. For deceleration characteristics, gender only influenced deceleration characteristics at middle speed scales (>25km/h), rather than the low speed scales (<25km/h). The two-tailed significance values indicate that driver occupancy (professional driver or non- professional driver) didn't have a significant influence on most acceleration and deceleration characteristics, except some middle speed classes. Gear type (automatic or manual) was only correlated with the acceleration characteristics at low speeds (<5km/h) and didn't influence deceleration to a remarkable extent.

Table 6.7 Mann-Whitney U Tests of Acceleration

	Mean Acceleration (m/s^2)					**Std Acceleration (m/s^2)**				
Speed (km/h)	2~5	5~15	15~25	25~35	35~45	2~5	5~15	15~25	25~35	35~45
Gender	.017	.057	.041	.002	.004	.001	.027	.083	.001	.000
Profession/non-prof.	.070	.117	.433	.058	.266	.015	.386	.680	.029	.117
Auto/manual gear	.044	.180	.397	.397	.778	.001	.502	.377	.044	.204
Before/after*	.041	.206	.673	.399	.770	.016	.538	.243	.399	.399

Note: 1. Underscoring numbers highlight the p-values smaller than 0.05.
2. 'Before/after' means that the participants filled in the DBQ before or after the in-car test.

Table 6.8 Mann-Whitney U Tests of Deceleration

	Mean Deceleration (m/s^2)					**Std Deceleration (m/s^2)**				
Speed (km/h)	2~5	5~15	15~25	25~35	35~45	2~5	5~15	15~25	25~35	35~45
Gender	.797	.135	.103	.008	.027	.959	.850	.363	.017	.110
Profession/non-prof.	.343	.343	.483	.007	.174	.837	.773	.805	.019	.063
Auto/ manual gear	.244	.120	.358	.306	.407	.258	.417	.129	.230	.289
Before/after	.085	.218	.581	.048	.364	.399	.974	.746	.032	.032

Note: 1. Underscoring numbers highlight the p-values smaller than 0.05.
2. 'Before/after' means that the participants filled in the DBQ before or after the in-car test.

18 participants filled in the DBQ before the in-car tests, and the other 12 participants finished DBQ after the tests. Mann-Whitney U Test results demonstrate that the sequence of DBQ and in-car tests has no significant influence on the drivers' acceleration and deceleration, except one or two speed classes. Because answering the DBQ questions did not apparently stimulate the participants to be more aware of their driving behavior, the participants did not change their driving style in the tests. This made the DBQ test results trustworthy.

6.4 Lane Changing Behavior Analysis

Compared with car following behavior, a lane change includes a more complicated mechanism which requires the driver to measure the available gap in terms of the relative speed and relative distance with the vehicles on the target lane. Lane changing is a complex process of decision-making. According to the driving situations and lane changing purposes, lane changes are usually classified as mandatory lane changes (MLC) and discretionary lane changes (DLC) (Sun and Elefteriadou, 2011). Knoop *et al*. (2012) analyzed the number of lane changes (per kilometer per hour) as a function of the density in the origin lane and in the target lane and found that drivers changed lanes in a strategic way by anticipating what would happen afterwards. Therefore, lane changing behavior is affected by many interdependent personal attributes (e.g., driver aggressiveness level) and impersonal attributes (e.g., traffic situation) and may differ greatly among drivers. To make a lane change, the driver may assess the necessity of a lane change, choose a target lane, and decide on gap acceptance, etc. Hereby, the probability of changing lanes under a certain condition depends largely on the driver characteristics and the traffic conditions. The correlation between the probability of changing lanes and driver attributes is revealed in this section.

During in-car tests, lane changing behavior was recorded through a manual analysis of video recordings, which is consistent with the method introduced by Zhao *et al*. (2012): a lane change is identified when the vehicle is firstly observed to move toward an adjacent lane and then fully drives at the center of the destination lane. Time spending on different lanes and the duration of lane changing were also recorded manually through the video observation. Overtaking can be simplified as sequentially changing lanes twice on two adjacent lanes in a short time. Through video observations, not only the number of lane changes was counted, but also the following information related to lane changing was recorded or checked:

- Lane changing category: MLC or DLC;
- Lane changing by crossing a solid line, or not;
- Turning the indicator before changing lanes or not;
- Checking mirrors before changing lanes, or not;
- Looking over his/her shoulder before changing lanes, or not;
- Overtaking for right side or left side;
- Aberrant lane changing: lane changing over three lanes.

Factor analysis was used to identify underlying factors that explained the correlation between the observed lane changing behavior and the DBQ aggressive score, etc. Eigenvalues (larger than 1) and scree plots (turning point) were used together to determine the number of extracted factors, as explained in Section 6.3.2. Finally, three components were extracted for the lane changing behavior data-set, as shown in Table 6.9.

Table 6.9 Three-factor rotated component matrix for lane changing behavior analysis

Variable	Factor 1	Factor 2	Factor 3
Aggressive Score		.727	
Driving experience in Year		.810	
Density	-.778		
Stop No./hour	-.565		
MLC	.973		
DLC	.974		
Crossing a solid line	.953		
Don't giving the turning indicator	.950		
Don't checking mirrors	.943		
Overtaking on the right side	.979		
Aberrant lane changes			.920
% of Variance	59.665	14.397	10.453

Note: The absolute values of factor loading below 0.40 were omitted for the sake of clarity.

The three-factor component matrix reveals that the variables related to traffic conditions are strongly negatively correlated with most lane changing behavior, and are all involved in Factor 1. The dense traffic can not only limit the number of lane changes, but also restrain some aberrant behavior, like crossing solid lines, forgetting to use the indicator and to check mirrors. Since dense traffic also restrains overtaking, it is not surprising to find less overtaking on the right side in a busy traffic situation. DBQ aggressive score and driving experience, which are highly correlated with each other, are both included in Factor 2. Aberrant lane changes are weakly related to other variables and can be considered as a kind of optional behavior. The total variance explained by this three-factor was 84.515%.

The correlation between lane changing behavior and other nominal variables was explored by Mann-Whitney U Tests, as shown in Table 6.10

Table 6.10 Mann-Whitney U Tests lane changing behavior analysis

	MLC	DLC	Crossing solid lines	Not using indicator	Not checking mirrors	Right side overtaking	Aberrant lane changes
Gender	<u>.003</u>	<u>.005</u>	<u>.003</u>	<u>.004</u>	<u>.001</u>	<u>.008</u>	.371
Profession/non-prof.	.086	.061	<u>.040</u>	<u>.027</u>	.127	.092	.790
Auto/manual gear	.152	.136	.112	.083	.190	.287	.396
Prior/after	.217	.142	.085	<u>.032</u>	.126	.192	.515

Note: Underscoring numbers highlight the p-values smaller than 0.05.

Similar to acceleration/deceleration behavior, lane changing behavior is markedly affected by gender, and weakly influenced by drivers' occupancy, even not related to vehicle gear type and the sequence of filling in the DBQ and doing the in-car tests. Based on these U tests and statistics, female drivers made significantly fewer lane changes (both MLC and DLC), and had fewer aberrant behaviors, such as missing indicator using, forgetting mirror checking, etc. The difference between professional drivers and non-professional drivers is only obvious in the behavior of crossing solid lines and checking mirrors. Professional drivers crossed solid lines more often, also checked the mirrors more frequently. The sequence of filling in the DBQ and in-car test does not have remarkable influence on lane changing behavior, except the use of the indicator.

6.5 Comparison between DBQ Answers and Actual Behavior

Factor analysis presented in the last two sections reveals the strong correlation between the aggressive score derived from the DBQ and the acceleration/deceleration, as well as lane changing behavior. The higher aggressive score indicates the larger acceleration/deceleration, the larger standard deviation of speed, the more often lane changing and the more aberrant behavior. The comparison between the DBQ answers and actual behavior is presented in this section.

The DBQ contains abundant information regarding driver behavior, some of which can be easily observed in reality. Therefore, several answers to the questions in the DBQ can be verified by video observations. However, some of them can't be easily observed in an in-car test, like selecting a wrong lane at an intersection. The comparison between DBQ answers and the actual behavior through video observations is summarized in Table 6.11. 'Consistent' means the observed behavior is consistent with the answer to the relevant question in DQB. 'Underestimated' and 'Overestimated' present the estimated frequency of the behavior in DBQ lower or higher than the observed ones respectively. Several findings in this section have implications for the simulation model development and calibration based on Chinese driver behavior.

- *Speed limit*

For the question 'Do you ignore the speed limit in urban areas when you are driving on a main road without much traffic?', 66.6% participants indicated 'Generally would not' or 'More likely would not'. During in-car tests, 30.6% trips had been recorded speeding, which is a quite high probability. It indicates that speed limits have been ignored by a large percentage of drivers in urban roads.

- *Crossing solid lines to make a lane change*

For the question 'Do you cross solid lines in order to change lanes?', 35.2% participants indicated 'never', 'nearly never', or 'seldom'. Based on in-car tests, crossing a solid line to change lanes in Changsha was found to have a quite high probability: 21.4%. The cause accounting for such a high probability will be explored in Chapter 7.

Table 6.11 Video observations and DBQ answer verification

Behavior	Summary of video observations	DBQ compared with the actual driving behavior			
		Consistent	Underestimated	Overestimated	Conclusion
Crossing a solid line to change lanes	21.4% lane changes with solid line crossing	70%	10%	20%	verified
Giving priority to pedestrians on zebra	Giving priority by deceleration, not fully stop.	80%	10%	10%	verified
Speeding	30.6% trips have been recorded speeding	60%	25%	15%	verified
Changing a lane due to the slow-moving vehicle front	Average time of lane changing is 1.1 times/min. 36% of lane changing is to achieve a high speed, a kind of DLC.	70%	15%	15%	verified
Using turning indicator when driving off or changing a lane	Drivers turned on the indicator before changing a lane with the probability 52.38%	60%	30%	10%	verified
Often checking the mirrors when going straight on	Average 10.5 times/hour	70%	25%	5%	verified
Keep driving on the left lane for long time	On three-lane roads, drivers spent 37.8% of time on the left lane, 39.2% on the median lane, and 22.9% on the right lane.	50%	30%	20%	Verified
Checking mirrors before driving off or changing a lane	Probability of checking mirror is 76.19%. Cannot clearly observe the behavior of looking over the shoulder.	70%	20%	10%	verified
Overtaking on the right side	46.67% of overtaking was on the right side. Then number of observed overtaking is only 20. Dense traffic situation in urban area limits the probability of overtaking.	80%	10%	10%	Partly verified
Using mobile phone	70% trips do not have any calls	90%	10%	0%	Not verified
Giving priority to vehicles from arterials	95% trips do not have conflict traffic	-	-	-	Not verified
Giving priority to straight on vehicles	95% trips do not have conflict traffic	-	-	-	Not verified

- *Probability of DLC*

The probability of DLC varied dramatically among participants. Male drivers with a high DBQ aggressive score were inclined to make a lane change more often to keep a high driving speed, compared with female drivers. In most cases, female drivers with a low DBQ aggressive score only made MLC lane changes. Lane changing models should designate different lane changing motivation for drivers to have different probability for lane changing.

- *Overtaking on the right side*

Overtaking was not so often observed in the in-car tests due to the dense traffic situations. The video observations revealed that 46.67% overtaking were executed on the right lane. Such high percentage of aberrant overtaking is a big threat to traffic safety. This common but aberrant overtaking behavior has to be introduced into simulation models to reproduce realistic traffic simulations.

- *Traffic volume distribution*

Left-most lanes were used more often in these tests than what the traffic rule proposes. On three-lane roads, 37.8% of the driving time was on the left lane, 39.2% on the median lane, and 22.9% on the right lane. Researchers should pay attention to this preference of drivers and adapt simulation models, for example by modifying the traffic flow distribution model to allocate more traffic on left-most lanes. The consequence of more traffic flow on the left-most lanes could lead to more difficulties for MLC to the left-turn lane and longer transition sections are required in reality.

6.6 Discussion and Conclusions

Based on the elaborately study of the in-car test videos and intensive analysis of the GPS data, the following research objectives have been achieved:

- *Validation of the conclusions drawn from the DBQ survey;*

The DBQ aggressive scores have been verified through in-car tests on urban roads in this Chapter. The correlation between the aggressive scores and the single question answers, like probability of crossing solid lines, overtaking on the right side, etc., has been developed. Some driver behavior investigated in the DBQ could be observed in the in-car test videos and most of the answers were consistent with the actual driving behavior. Quite a lot of driver behavior in DBQ could not be verified due to the limitations of the videos, like the short observation time.

- *Exploration of the relation between the DBQ scores and driver behavior on urban roads;*

DBQ aggressive scores, as a clustered concept, were determined according to the answers to the DBQ. In the in-car tests, DBQ aggressive score can effectively represent the driving style in reality. Compared to drivers with low aggressive scores in the DBQ, drivers with a high aggressive score accelerated more rapidly, changed lanes more frequently, and carried out more hard braking, which can be considered as a kind of unsteady driving style. The drivers with high aggressive scores also represent a more aggressive driving strategy, because they usually spent more time on the left lane, made aberrant lane changes more frequently, etc.

- *Collection of data from driving in field*

Besides the detailed speed and acceleration/deceleration profiles deduced from the GPS data of every test trip, the behavior of lane changing was analyzed through video observations. Some information related to lane changing was also recorded or checked, such turning on the indicator and checking the mirrors before making a lane change.

- *Category of driving type*

Factor analysis has been used to develop a four-factor structure for the in-car test data set. Based on the four factor scores, four driving types have been classified. Acceleration at low speed and deceleration at high speed provide the main separation between driving types. It has been also revealed that the correlation among lane changing behavior, the traffic situation and the DBQ aggressive score.

- *A solid foundation for the calibration of simulation programs*

The acceleration/deceleration and lane changing characteristics of every driving type distinguished in this chapter developed a basis for the calibration of microscopic simulation models. These models can be calibrated based on the driving characteristics of different driving styles. Some additional information, such as the use of the left-most lane, overtaking on the right side, can also offer useful information for the improvement of simulation models.

- *Some other interesting findings*

Gender was found to be significantly relevant to driving style in reality; even the DBQ aggressive scores derived for males and females did not vary to a remarkable extent (see Chapter 5). Male drivers had more rapid accelerations, more frequent lane changing than female drivers. Male and female drivers did not show too much difference in deceleration, especially at low speed (<25km/h).

Compared with gender, the links between driving characteristics and driver occupancy (professional vs. non-professional) and vehicle gear types (automatic vs. manual) were relatively weak. The sequence of questionnaire and the test trip (DBQ is before the test or the reverse) did not have a significant influence on the driver behavior. Participants still drove in their own way, which makes the in-car test results more convincing.

The traffic density was negatively associated with the drivers' acceleration/deceleration and lane changing behavior. The underlying reason should be that the dense traffic constrained drivers' acceleration and limited lane changing possibilities, and drivers had a low probability to achieve their desired acceleration and desired speed.

Though factor analysis and K-Means cluster analysis, four driving styles were classified to represent the distinct driving characteristics. Different test trips made by the same drivers mostly belong to the same driving type. The plausible reason is that driver behavior is stable when the traffic situations and driving purposes do not vary too much. At the same time, the stability of driving type can be considered as evidence for the rationality of this categorization method.

The DBQ survey made in China revealed a quite high frequency of traffic rule offences, which was also verified through the in-car test: a large percentage of speeding, high frequency of aberrant lane changes, overtaking on the right side, and high probability of crossing solid lines. Besides these aberrant driver behaviors, the findings about quite long time use of the left-most lane and a high probability of DLC provide addition information for simulation model development and calibration. For example, the traffic flow distribution model should be calibrated to arrange more traffic on the left-most lane; some types of drivers should be simulated with high frequency of lane changing.

The main limitation of in-car tests is the consistency of the test driving behavior with the actual driving behavior. The presence of the apparatus and being aware of a test both might make the participants drive differently from their regular way. To overcome this limitation, a possible method is to analyze the driving behavior of other drivers on the videos. However, this exceeds the research scope of this dissertation.

In summary, DBQ scores have valid, objective and plausible links with the driving behavior observed in the in-car tests; most driver behaviors which can be analyzed through video observations are consistent with the answers made in the DBQ; some answers in the DBQ (e.g. reaction to traffic signal, mobile phone using) are not easily verified by in-car tests due to the short observation time (half an hour); in-car tests are an effective method to get abundant data relevant to actual driver behavior; the driving type classified by factor analysis and K-Means cluster analysis not only distinguish driving styles, but are also associated with driving attitudes (DBQ score), rather than driving skills.

Chapter 7

Focus Group Findings[4]

7.1 Introduction

As explained in Chapter 2, China became the second biggest vehicle country and the largest vehicle market in the world since 2011. The vehicle ownership and the number of drivers both increased dramatically in the past decade. The driving custom and driver behavior in China are considered to be different from those in Western countries where motorized transport has developed for more than 100 years. Field observations presented in Chapter 4 have shown that the saturation flow rates at Chinese signalized intersections are about 20% to 30% lower than the values at similar intersections in the Netherlands. The Driver Behavior Questionnaire (DBQ) survey introduced in Chapter 5 reveals the distinctly difference in driver behavior between China and the Netherlands. The in-car tests shown in Chapter 6 confirm the result of the DBQ and showed a lot of aberrant driving behavior of the Chinese drivers.

Regarding Chinese driver behavior in urban traffic situations, several research questions still do not have distinct answers:

- What are drivers' main opinions of driving in China;
- What factors can significantly influence the driver behavior in car following;
- What factors remarkably influence the Chinese drivers' decisions concerning lane changing and overtaking;
- What is the common way of Chinese drivers to react to signal transition;
- What do Chinese drivers think about traffic rules, especially priority rules?

The full answers to these questions are not easy to be found through the often used investigation methods, like external observations, DBQ, or simulator tests. Driver behavior observed in field can be considered as veracious, but is usually limited to a short time period of data collecting (e.g. video observation, trajectory analysis) or a limited number of drivers (e.g. probe vehicle) (Ciuffo *et al*., 2008). DBQ survey is a simple way to measure

[4] This chapter is based on the paper: Driver Behavior at Urban Roads in China: Focus Group Findings (2014), by Li J., H. van Zuylen, E. van der Horst, *Proceedings of Transportation Research Board 93rd Annual Meeting*, Paper ID: 14-4617, Washington, D.C.

self-reported driver behavior (Davey *et al*., 2007; de Winter and Dodou, 2010; Kircher and Andersson, 2013; Lajunen *et al*., 2004). But the research results obtained from DBQ usually require to be confirmed through the driving observations. The other limitation of DBQ is that it gives too limited information about drivers' opinions and thinking process. A simulator can easily create different driving scenarios and collect plenty of relevant data from the testing driver (Sivak *et al*., 1989c). But the fictitious traffic situation provided by the simulator decreases the veracity of the data. Focus groups can overcome some of these limitations and can be considered as an additional investigation method.

The application of focus groups in research can be cast back to the 1930s when social scientists wanted to move from close-ended interviews to open discussions. Focus groups originally used by social scientists can assist in understanding what people think about an issue (Rubin, 1996). At the beginning of 21 century, focus groups were introduced into transportation study and become a practical way to obtain qualitative information about people' opinions. In Hong Kong, Wissinger *et al*. (2000) organized focus group sessions to investigate the attitudes of the public to red signal cameras. Focus groups conducted by Hostovsky *et al*. (2004) were to investigate commuter drivers' perceptions of the level of service of freeways. Sun and Elefteriadou (2011) studied lane changing behavior and ramp merging behavior on freeways through focus groups; and furthermore the participating drivers were categorized according to their background information and verbal responses. Compared with other investigation methods, focus groups have the following advantages:

- The permissive environment can make participants feel comfortable and disclose themselves;
- Open discussions can reveal drivers' comprehensive opinions of driving in China;
- Casting back to know how do drivers develop their driving behavior over a long period;
- Overcoming the knowledge limitations of the organizer to get integrated information about drivers' decisions making;

Focus groups can help to understand drivers' opinions of driving, to identify the factors important to drivers' decisions making, and to explore the effective measures for driver behavior improvement. The remaining part of this chapter is composed of four sections. In next section, a description of the focus group experiment is presented. Section 7.3 presents the discussion on driver behavior with the most important contents highlighted. In Section 7.4, the conclusions are drawn from this survey and the relevance to the further study is presented.

7.2 Methodology

This section describes the organization of the focus groups and presents the main questions discussed during the sessions

7.2.1 Setting up focus groups

The focus group study was carried out in Changsha, a city in the middle of China with 7 million inhabitants. The participants were selected from the respondents of the previous DBQ survey with diverse background regarding gender, age, driving experience and occupancy. More details about the DBQ survey can be found in Chapter 5 and (Li *et al*., 2014). Totally, 35 participants were divided into 6 sub-groups and participated a 2-hour focus group session respectively. In each session, participants were also required to complete two survey forms associated with lane changing and overtaking behavior. All focus group sessions were held in June, 2013.

7.2.2 Participants

Totally 6 focus group sessions involving 35 participants (28 males and 7 females; 25–50 years) were organized in this survey. The largest proportion of vehicles driven by the participants was reported to be their own vehicle (71.4%), and a small proportion was from a company or institute (22.9%) or others (5.7%), etc. The participants had different education background: Professional education 10 (28.6%), Bachelor 11 (31.4%), Master or higher than Master 6 (17.1%), and Others 8 (22.9%). Most of the participants (25.7%) were Professional Persons; Administrative staff and Professional driver both constitute 20%. Most participants, i.e. 60%, indicated that they enjoy driving. A small part of participants either did not have special feeling for driving (28.6%), or dislike driving (11.4%). In Table 7.1, some basic information about the focus group participants is summarized, in comparison with the whole Chinese DBQ data sample (see Chapter 5).

Table 7.1 Characteristics of the Chinese DBQ sample and focus group sample

Item	DBQ sample (n =215)	Focus group (n=35)	Note
Mean age (SD)	36.01 (8.05)	40.2 (5.7)	
Males (%)	80.0	80.0	
Professional driver (%)	4.65	22.9	
Mean driving experience in years (SD)	6.19 (6.33)	10.2(8.6)	
Enjoy driving (SD)	6.92 (2.14)	7.5(2.2)	1= dislike; 10 = enjoy very much
Self-estimated driving type (SD)	3.95 (2.08)	4.1(2.3)	1 = very conservative; 10 = very aggressive
Others-estimated driving type (SD)	4.25 (2.14)	4.3 (2.5)	1 = very conservative; 10 = very aggressive
Self-estimated driving skill	6.44 (2.15)	7.3(2.0)	1 = very poor; 10 = very excellent
Offences recording in last year (%)	57.7	71.4	
Accidents involved in previous 5 years (%)	51.2	62.9	
DBQ aggressive score	69.96 (13.24)	71.1(12.8)	

In order to explore how drivers develop their behavior over a long period, several experienced (driving license >20 years) and professional drivers were invited to participate the focus group sessions. For this reason, the percentage of professional driver, the average driving experience and self-estimated driving skill in the focus group sample are all larger than those in the whole Chinese DBQ sample. The long driving exposure may account for the high percentage of offences recording and accidents involvement. However, these two data samples are similar to each other in other characteristics, such as ‘Enjoy driving’, ‘Self-estimated driving type’, and ‘Others-estimated driving type’.

The Mann-Whitney U test was used to determine whether there is a significant difference in aggressive scores between Chinese DBQ sample and focus group sample based on the null hypotheses: *There is no significant difference in the aggressive scores between the two data samples*. According to the test result, the significance *p*-values of test is 0.838, larger than 0.05, and the null hypotheses can't be rejected. It indicates that there is not a significant difference exists in aggressive scores between these two driver samples.

7.2.3 Focus group experimental design

Focus group discussions were around questions of three categories: opening questions, practical questions and ending questions. The opening question is to encourage people to relax and start talking. The practical questions were related to five aspects of driving: car following, lane changing, overtaking, reaction to traffic signals, implementing traffic rules, which are all relevant to driver behavior models. The main purposes of these questions are to identify the factors that influence driver behavior significantly and to reveal how to improve driver behavior in practice. The ending question is to make sure that all important topics have been covered. The procedure of the focus group sessions are described in Figure 7.1. The questions discussed in the focus group sessions are listed in Appendix D.

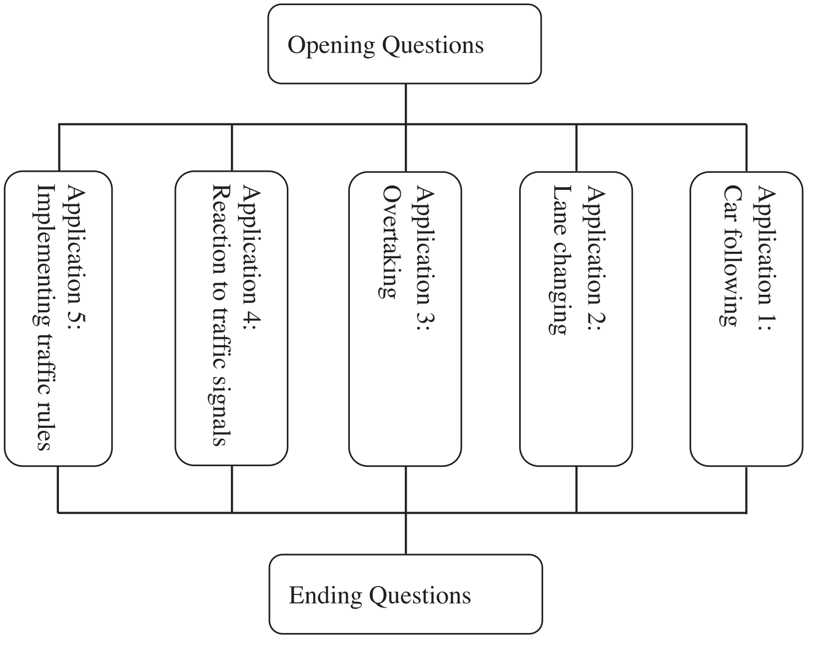


Figure 7.1 Procedure of focus group sessions

7.3 Focus Group Discussion

During focus group sessions, the following data were collected:

- Voice recordings of the 2-hours sessions,
- Answers to DBQ, and

- Two additional investigation tables regarding lane changing and overtaking.

Differing from the focus group studies conducted by Sun and Elefteriadou (2011) who categorized participating drivers according to their background information and verbal responses. It was found in this study that the opening discussion can make participants easily influence each other. Thus, the opinions expressed verbally cannot be distinctly ascribed to individual perceptions. In this section, the discussion about every sub-topic is concluded and the important or novel opinions are highlighted.

7.3.1 Opening questions

In order to make participants relax, the opening questions only consist of several general questions about driving:

- What do you think about Chinese people's driving behavior? Why?
- Is your driving style conservative or aggressive?
- What factor can significantly influence your driving style?
- Do you enjoy driving? Why?

Most of the participants thought Chinese drivers' behavior is not so well in terms of the high percentage of offences and aberrant driving behaviors, like sudden or forced lane changing without indication signal, refusing to yield to the conflict vehicle which has the priority. For this situation, several causes were presented:

1) Short motorization history

Just after 2000, the vehicle ownership keeps increasing dramatically every year, and vehicles are becoming an ordinary household product. Such a short motorization history makes that the related education system, testing system, and law system all in a developing phase.

2) High proportion of novice drivers

In China, about one third of the drivers are novices who have limited knowledge in evaluating the driving environment and conditions compared with the experienced drivers. So these novice drivers behave quite heterogeneously: *some are quite aggressive and some drive too conservatively*.

3) Stricter monitoring can help drivers to develop better driving behavior.

The traffic monitoring and management systems in China are also in the development stage. If the offence isn't penalized, more drivers will continue to infringe/ violate the rules. Two participants indicated they drove quite differently in different Chinese cities with difference traffic monitoring levels.

4) Influenced by other drivers

Almost all of the participants expressed that they fully complied with traffic rules and drove in a quite courteous way when they just got a driving license. But other drivers did not return this courtesy and even made them feel difficult in driving. Gradually, these participants accepted a more aggressive driving style.

5) Very few drivers are aware of their own aggressive driver behavior.

Even most participants thought Chinese drivers' driving behavior is not good, only 5 of the 35 participants admitted they are somewhat aggressive in driving and all the other participants considered them as a conservative or common driver.

Participants explained that their *driving style can be influenced by lots of different factors*. The most frequently mentioned factors are *traffic conditions, weather, driving tasks, local traffic rule enforcement system*, *and personal mood*. In a hurry and congested situation, the driving style can become more aggressive than that in a normal situation. Based on the discussions, *the influence of personal mood on driving style can vary among different drivers*. Some participants indicated that a cheerful mood can give them more patience in driving. But some others said that they easily make driving errors in a cheerful status. Some participants stated they become more aggressive when they are tired because they want to arrive at the destination as soon as possible; others expressed that they would be more careful in driving to avoid traffic incidents when they are tired.

21 of the 28 male participants denoted they enjoyed driving very much with different reasons, such as: convenience, feeling of freedom, pleasure of sports, and the quiet private space. All of the 7 female participants expressed that they dislike or don't have special feeling with driving. The causes for the dislike of driving are congestion, difficulty in parking, risk of accidents, etc. It can be concluded from these focus group discussions that *most male drivers like driving; and most female drivers don't*.

7.3.2 Application 1: Car following behavior

In the focus group sessions, car following was explained as driving behind another vehicle with a short distance. The main questions about car following are:

- What issues are important to 'car following'?
- What factor is important to the distance which you keep with the preceding vehicle?
- In what cases can you keep patient in car following? What situations can easily make you lose patience?

To 'car following', the first important issue is *'safe distance to the preceding vehicle'* . The 'safe distance' depends on drivers' personal characteristics, but also on traffic situations:

- In order to prevent a forced lane change under congested traffic conditions, participants prefer to keep a quite short distance from the preceding vehicle.
- But in an uncongested situation and driving at a high speed, participants are inclined to keep a larger headway. They worry that aberrant behavior of other drivers can result in quite serious traffic accidents at a high speed. For instance, an adjacent driver in front of them changes lanes suddenly; or the preceding vehicle brakes sharply.

These descriptions are consistent with the common traffic phenomena in China: drivers keep quite short space headways in a bottleneck; but after passing the bottleneck, the drivers seem to relax and keep quite long headways.

To 'car following', the second important issue is *'sufficient view distance'*. The experienced drivers stated they often try to observe a long distance in front of the preceding vehicle, so that they can get a better view and make proper decisions in time. *In order to have a wide* *view, they often drive along the marking line rather than in the middle of the lane*. Compared with experienced drivers, novices mainly concentrate on the preceding vehicle and pay less attention to the whole traffic surroundings.

To 'car following', the third important issue is *'accelerating slowly on up-hill road sections'*. Experienced drivers described that they do not dare to accelerate quickly in dense traffic on a up-slope road section, because there is potential risk of rear-end collisions if the vehicle in front suddenly brakes while their foot are still on the gas pedal. On a down-slope section, it is safe even driving at a high speed because drivers usually don't put their foot on the gas pedal and can brake quickly in the case of urgency.

The distance to the preceding vehicle, as a key parameter in car following models, can be generally influenced by several factors listed in Figure 7.2. In order to know what the participants think about these factors, an additional table was designed in advance and participants were required to estimate the importance level for every factor. Based on the participants' answers, the average importance level and the standard deviation were calculated and shown in Table 7.2.

Table 7.2 Factors influencing car following distance (1 = least important, 5 = most important)

Possible Factors	Average Importance (Max=5)	Importance SD
Your Speed	3.1	1.5
Speed of the preceding vehicle	3.8	1.2
Driving task and personal mood	3.1	1.5
Road configuration: slope, lane width, curve	3.3	1.3
Category of the preceding vehicle (bus, truck)	3.8	1.4
Pavement conditions	3.4	1.2
Weather	3.5	1.3
Signaling conditions (evening/daytime)	3.4	1.4

The speed of the preceding vehicle and the category of the preceding vehicle (bus, truck) are identified by the participants as the two most important factors to the distance keeping from the preceding vehicle. Even though the importance of the other factors listed in Table 7.2 doesn't vary remarkably, factors related to driver self conditions (e.g., own speed, driving task and mood) seem less important compared with the environmental related factors (e.g., pavement, weather, and signaling conditions). So it can be preliminarily concluded that *drivers are more sensitive to the environmental factors than the personal factors*.

Participants agreed that three factors influence their patience in car following significantly. *The first factor is time pressure*. If they are in a hurry on the way to their destination, they will change lanes more often to increase their driving speed. *The second factor is the traffic condition***.** If the traffic volume is high, drivers want to achieve a high speed and shorten waiting time in a queue, then make lane changing more often. But if it is fully congested, an acceptable gap is also not easy to be found and changing a lane doesn't make any difference for their driving condition. Therefore, most drivers have to keep patient in a car following mode. *The third factor is the type of the preceding vehicle*. Most of participants stated that they are unwilling to follow four kinds of vehicles: novices (In the first year of driving license, the novice should have a yellow sticker on the back of his/her vehicle), taxi, bus, truck, because these vehicles have more aberrant behaviors.

7.3.3 Application 2: Lane changing behavior

As verified in Chapter 6, some Chinese drivers change lanes quite frequently. Irregular lane changes can result in disturbance to the traffic flow and consequently reduce traffic capacity (More details are shown in Chapter 4). The questions related to lane changing comprise:

- What issues are most important to "lane changing"?
- Which kind of lane changing behavior do you dislike?
- Do you accelerate or decelerate while making a lane changing?
- Cooperation and competition in lane changing
- Likelihood of lane changing

Most participants stated that *the available safe gap is the most important issue to lane changing*. Participants listed the most frequently observed aberrant lane changing behaviors: *no indication signal for lane changing, forced lane changing, and long-time driving above the marking line between lanes*.

Quite significant differences exist in lane changing behavior between male and female participants. Most male participants told that they always accelerate during lane changing because they want to finish the lane change as soon as possible. On the contrary, most female participants stated that they are inclined to decelerate in a lane change so that they can easily stop this maneuver at any moment if necessary. Also some participants stated that they often accelerate when changing lanes in free flow, and decelerate in dense flow. They explained the reasons: hesitation in lane changing at a high speed easily lead to a rear-end collision; a lane change in dense traffic has to be done slowly because of more interactions with the following vehicle.

1. Cooperation and competition in lane changing

The interactions between vehicles involved in a lane change can be described as either cooperation (the follower courteously yields to create a gap and allows the leader to move to the front of him/her) or competition (the follower brushes aside the intention of the leader, but the leader still try to make a gap for lane changing) (Sun and Elefteriadou, 2010). In the focus group sessions, the participants were required to describe their actions in two scenarios.

Scenario 1. You need to change a lane

Do you operate differently in two lane changing situations: changing to the right lane or to the left one? Does any difference exist between normal and congested traffic situations? (See Figure 7.2*)*

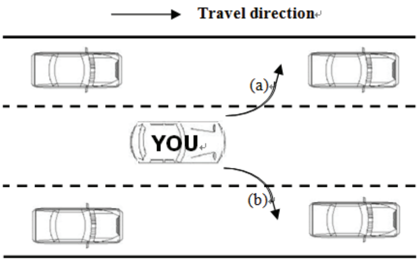


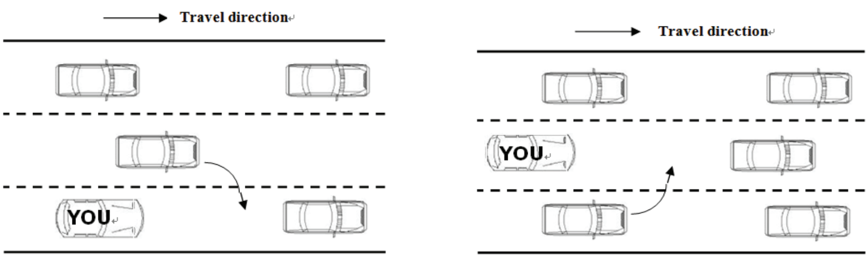
Figure 7.2 Lane changing to different directions
Note: (a) You are planning to merge to the left-most lane; (b) You are planning to merge to the right-most lane.

Participants explained that lane changing to the right-most lane is more difficult and requires a longer gap than to the left-most lane. One reason is based on the fact: the blind angle on the right side of the vehicle is larger than the left side one (for a vehicle with the steer at left). The other reason is that the right lane generally has more disturbances, e.g. holes in the pavement, pedestrians, mopeds and electric bicycles. In conclusion, *the critical gap for lane changing to the right side should be much larger than that for the left side*.

In urban areas, the difference in lane changing between different traffic situations is represented by the different locations where a lane changing decision is made. *In dense flow, participants worry about less chance to change a lane and start lane changing much earlier than under a free-flow condition*.

Scenario 2. Forced lane changing in front of you

Do your react differently in the following two lane changing scenarios:



(a) (b)

Figure 7.3 Reaction to forced lane changing behavior
Note: (a) You are on the right-most lane and the other vehicle in the left lane is attempting to merge in front of you; (b) You are on the median lane and the other vehicle is planning to merge in front of you.

For the first scenario, most participants expressed that they are willing to yield to create an available gap for a forced lane change when they are on the right-most lane because they think the driver changing a lane to the right possibly wants to turn to the curb-side lane and exit this street. But they are not willing to create a gap to a forced lane changing when they are in the median lane because the other vehicle disturbs them to a certain extent. Few participants (6/35) denoted that they always refuse to cooperate with other drivers' force lane changing. In short, *forced lane changing to the right-most lane can easily get cooperation from other drivers*.

2. Likelihood of a lane change

In order to identify the importance of the potential factors to lane changing, participants were asked to evaluate the level of likelihood (from 1 to 5) of initiating a lane change for each listed scenario according to their driving experience. For every given scenario, there are two different driving tasks: for commuting, and for leisure. The traffic environment is assumed to be on a 6-lane urban road. The results are shown in Figure 7.3.

Table 7.3 Likelihood level of making a lane change (1 = generally would not, 5 = generally would)

	Commuting		**Leisure**	
Scenario	Average	SD	Average	SD
Stopped bus	3.8	1.3	3.1	1.4
Another vehicle merging into your lane	2.5	1.5	2.0	1.2
Slow-moving vehicle ahead	4.0	1.2	3.7	1.2
Shorter queue of waiting vehicles on another lane	3.6	1.2	3.2	1.2
Bus or truck in front of you	3.7	1.2	3.5	1.5
Undesirable pavement conditions	3.6	1.4	3.3	1.4

The front slow-moving vehicle is the most important inducement to a lane change. In commuting, stopped bus and preceding vehicle type (bus or truck) are the other two factors with quite high likelihood to stimulate a lane change. Compared with other scenarios, vehicle merging has a low likelihood to make other driver change a lane. In Table 7.3, the likelihood of lane changing in a leisure trip is much lower than in a commuting trip in every given scenario, which proves again *driving behavior can vary to certain extent in terms of driving targets*.

7.3.4 Application 3: Overtaking behavior

In the focus group sessions, overtaking is defined as passing another vehicle. Several questions related to overtaking are discussed:

- What factors are most important to "overtaking"?
- What kind of overtaking behaviors do you dislike?
- What do you think about 'overtaking on the right side'?

Participants agreed that *proper speed and a broad view for the whole traffic surrounding are critical for overtaking*. Some experienced drivers emphasized sufficient preparation should be made to inform the preceding vehicle that it will be overtaken. They often signal by flashing the headlights and hooting the horn. These behaviors are proposed by the Chinese Regulation on Road Traffic Safety (2013), but are considered as aggressive in Western drivers' eyes.

Participants disliked two kinds of overtaking: after starting overtaking, the front vehicle also accelerates, and forced overtaking without a sufficient gap. China is a country 'driving on the right side'. However, *overtaking on the right side and driving on the overtaking lane for long time are quite common in urban areas in China*. The participants gave several reasons to explain these behaviors:

1) There are often more lanes on urban roads than on highways, so *forbidden overtaking on the right side is not an important traffic rule in urban areas*;

2) The left-most lane has fewer disturbances and better pavement than the right-most lane, which both stimulate drivers to drive more often on the left-most lane. Consequently, *the chance of overtaking on the left side lane is too limited*.

3) Most of the participants indicated *it is not so important to change back to the original lane after overtaking in urban areas*. They still drive on the overtaking lane for quite a long time because of less disturbances and better pavement.

4) According to the participants' explanation, *it is not emphasized in the driving course that they should not stay on the left-most lane for a long time on urban roads*.

Due to the reasons given above, most participants do not consider 'overtaking on the right side and driving on the overtaking lane for long time in urban areas' as a kind of inappropriate driving behavior.

7.3.5 Application 4: Reaction to traffic signals

Traffic management and driver behavior at intersections are critical to the performance of the whole network in urban areas. In the focus group sessions, reaction to traffic signals was discussed through several key questions.

- What are you doing during the red phase when you are the first driver in the queue?
- What are your general reactions when you are the first driver in the queue and see the signal turns to green?
- What are your general reactions when you see the signal turning to yellow?
- What factors can influence your reaction to traffic signal? Are you aware of some mistakes in your reaction to the signal?
- What is your attitude to a conflicting vehicle that is still remaining at the intersection at the beginning of a green phase?

Q1. What are you doing during a red phase when you are the first driver in the queue?

7 out of 35 participants' vehicles have an automatic gear. However most of the participants' are similar to each other when they are waiting for a green phase. During the red phase, they often move the gear to the neutral position and still keep their feet on the brake. If the cycle time is long, they will move the gear to parking position and even take the hand brake. In

short, *when waiting for a green time, the actions of the automatic gear car drivers are quite similar to those of the manual gear car drivers*.

The difference of the professional drivers is that they not only observe the signal for their lanes, but also pay attention to the signals and movement on the other lanes. *When the signal turns to green, professional drivers can have shorter reaction time than other drivers*. In China, most signalized intersections don't have an all-red clearance phase and signals are installed on the far side of the intersection rather than above the stop line. It is possible for the drivers to observe the signal for the other directions and to prepare to accelerate their vehicles before the signal for the other directions turns to yellow.

Q2. What are your general reactions when you are the first driver in the queue and see the signal turns to green?

Most of the participants stated that they will first release the brake, then check if there are still pedestrians in the conflict area, and finally accelerate. Differing from novice drivers, experienced drivers care about their vision. If their vision is obstructed by another vehicle, they do not dare to accelerate quickly because there are possibly some conflicting vehicles or pedestrians hidden. *Most participants told that they are very careful at the beginning of green phase and do not dare to accelerate quickly due to possible conflicting traffic flows*.

Q3. What are your general reactions when you see the signal turning to yellow?

Many participants are not clear about the appropriate actions during the yellow phase. To this question, 9 participants admitted that they always speed up, 21 participants said they always decelerate, and only 5 participants indicated that their actions depend on their speed and distance to the stop line.

Participants said they did not get any special instruction or training regarding the reaction to yellow phase from their driving license course and the coach often emphasizes careful driving and braking in any urgent case in an intersection area. Most participants agreed that crossing stop line in yellow phase is a potential cause for traffic accidents.

Q4. What factors can influence your reaction to traffic signals? Are you aware of some mistakes in your reaction to the signal?

Most participants agreed that *the location of the signal, the definition of stop line markings, private activities, and the type and behavior of the preceding vehicle can influence their reaction to signal to a certain extent*. In China, signals are often installed on the far side of the approach, rather than above or beside the stop line. Drivers' view can be easily blocked by a bus, even by a SUV under dense traffic conditions. At some intersections, the stop line is too vague to be identified quickly, which can also influence the reaction to traffic signals. Many participants admitted that, while they are waiting for a signal, their attention can be easily distracted by some private activities, like using mobile phone, chatting with other passengers, etc. 5 participants had the experience of driving through a red light because they only focused on the preceding vehicle and ignored the signal transition.

Q5. What is your attitude to a conflicting vehicle that is still remaining at the intersection at the beginning of a green phase?

Only 14 out of the 35 participants told that they always give priority to these conflicting vehicles in such a scenario with decelerating or driving around these vehicles, very few participants said that they will fully stop. 18 participants explained that they will not give the priority when they are in a hurry or if other drivers behind them squeeze them. 3 participants showed they never gave priority to the remaining conflicting vehicles. *To sum up, participants' attitude to the remaining conflicting vehicles at a signalized intersection is diverse and the priority rule in this situation is quite unclear to most drivers.*

Q6. What's your opinion of the traffic signal design in Changsha?

All participants are not professional persons in traffic management and only gave some quite personal opinions about the traffic signal design in China, as listed as follows:

1) Some participants said it is difficult to compare the signal design in Changsha with other cities or countries to them, but they still think traffic design and management in Changsha has been improved quite a lot compared with before.

2) The traffic control system in Changsha is expected to be replaced by an actuated or adaptive traffic control system. Participants think the green time is wasted too much at some intersections and waiting time in some traffic direction is too long.

3) Signal lights and stop lines should be improved to be easily distinguished by drivers.

7.3.6 Application 5: Knowledge of traffic rules

Traffic rules, as an important component of traffic management, are not only critical to traffic safety, but also relevant to simulation models. Most simulation models comprise the official traffic rules, but in reality drivers ignore these rules in some cases. Several questions associated with traffic rules, especial with priority rules were discussed in the focus group sessions.

- Tell some rules related to priority. Are these rules important? Why?
- Identifying priority signs.
- Do you think some traffic rules are important and others less important? Why?
- What offences do you often make?

Q1. Tell some rules related to priority. Are these rules important? Why?

Most participants only knew two priority rules: turning vehicles should always give priority to through going vehicles and vehicles should always give priority to pedestrians on 'pedestrian crossings '. Only 4 participants knew that drivers should give priority to the vehicles coming from the right side. The participants were required to rank the priority of three vehicles in three scenarios, as shown as follows:

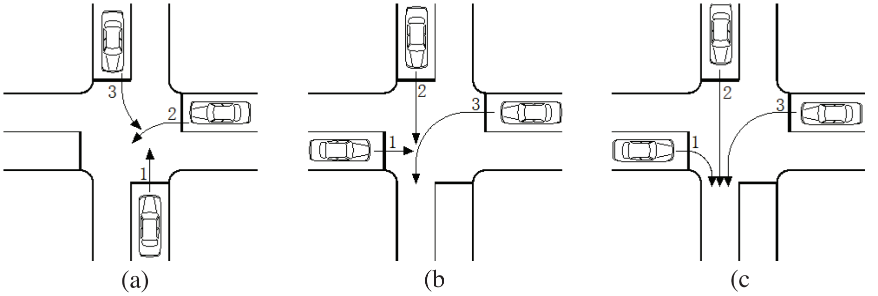


Figure 7.4 Conflicting traffic flows at three scenarios

In China, the priority rules for an un-signalized intersection (without any priority sign or traffic police directing in field) are listed as follows (Chinese Regulation on Road Traffic Safety, 2013)：

1. Vehicles from the left side give priority to the vehicles from the right side;
2. Turning vehicles give priority to the through going vehicles；
3. Turning right vehicles give priority to the turning left vehicles if they are from the opposite direction.

When the traffic situation can match more than one rule, the later rule should be implemented. For example, scenario (a) matches both rule 1 and rule 2, the rule 2 should be enforced, i.e. vehicle 2 should give priority to vehicle 1.

But in most Western countries, like the Netherlands – which was used as a comparison -, the priority rules for the same un-signalized intersection are simple, as described as follows:

1. Vehicles from the left side give priority to the vehicles from the right side;
2. Turning vehicles give priority to the **oncoming** through going vehicles.

In terms of these two different priority rule settings, the priority can be ranked as:

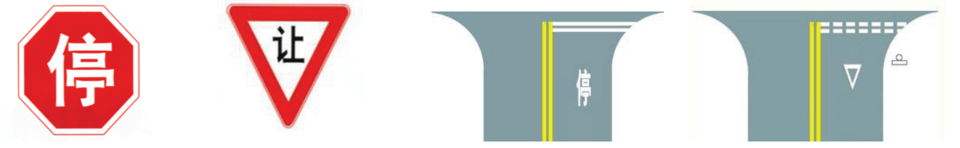
Table 7.4 Priority in different scenarios

Scenario	**(a)**	**(b)**	**(c)**
China	**1>3>2**	**1>2>3**	**2>3>1**
the Netherlands	3>2>1>3, courtliness	**1>2>3**	**1>2>3**

There was only one participant who gave the correct answers for all three scenarios in terms of the Chinese priority rules. *All the other 34 participants were not clear about the priority rules and even the experienced drivers said they never learned these priority rules*. In reality, '**courtesy**' is proposed mostly for solving the conflict in driving, not only by driving coaches, but also by traffic police and newspaper, etc. Through the focus group discussion, all participants agreed on the importance of priority rules, and they also found that the rules in Western countries are much easier to be implemented in practice. In conclusion, *priority rules in China are not so easy to be implemented in practice and Chinese drivers' knowledge of these priority rules is very limited*.

Q2. Identifying priority signs

All participants were asked to write down the meaning of several traffic signs related to priority rules. These signs are to give priority by an obligatory full stop or deceleration; they are on the road pavement or on the road side respectively, as shown in Figure 7.5:



(a) (b) (c) (d)

Figure 7.5 Priority signs: give priority by an obligatory stop (a, c), and by deceleration (b, d)

The answers given by the 35 participants are rather peculiar: only 2 persons from the 35 participants could give the correct answers to the four priority signs. More details about the answers are shown in Table 7.5.

Table 7.5 Answers to recognizing priority signs

Location	Sign	Correct Answer	Ambiguous Answer	False Answer	Unknown	Never Seen
On road side	Give priority by stop	4	0	9	12	10
	Give priority by deceleration	3	3	1	14	14
On the road pavement	Give priority by stop	5	1	11	17	1
	Give priority by deceleration	4	14	1	15	1

Most participants gave wrong answers, or admitted they didn't know or had never seen them. A few participants only gave ambiguous answers, like deceleration, carefully driving. 22 participants even didn't believe that there is a traffic rule to give priority by a fully stop. It can be conclude that *most participants are weak in recognizing the traffic signs related to priority rules*.

The participants were shown with several other common traffic signs: forbidden stopping, forbidden parking, one-way street, and forbidden driving respectively. Except the 'forbidden parking' sign, most of the participants did not know the other signs clearly. After such a small test in focus group sessions, *most participants admitted they didn't have the habit to search for traffic signs, especially signs on the road pavement*. Participants revealed that they don't reinforce their memory about some of the driving rules and traffic signs after getting the driving license.

The evidence presented in this Chapter also illustrates that *the present Chinese driving training and testing system is not sufficient to ensure that all candidates can become a safe* *and competent driver*. The main reason could be the separation between the theory study and the practical training: most candidates study traffic rules for a theoretical test in isolation rather than integrated with practical driving. As suggested by Emmerson (2008), an appropriate driving education system should provide the new drivers with the right skills and experience to be safe drivers. Risky behaviors which can lead to accidents should be sufficiently addressed through driving education. Usually, drivers only got limited driving experience from the limited amount of practical courses prior to obtaining a full license. In order to overcome the absence of experience, Emmerson (2008) also encouraged drivers to take additional training for a full range of driving conditions after getting a license.

Another rather peculiar finding is that *the word 禁停- 'Jin Ting' -can mean both 'forbidden stopping' and 'forbidden parking' in Chinese.* The double meaning of the sign '禁停' leads to confusion in understanding, namely people (even some traffic policemen) who know the name of the sign, but maybe do not know the meaning correctly.

Q3. Do you think some traffic rules are important and others less important? Why?

Most participants agreed that *all traffic rules are important, especially the traffic rules related to traffic signals*. However, a part of participants (about twenty) found *some rules are irrational*, for example too low speed limit (e.g. 40km/h) on a national road, too long solid line markings between lanes to forbid changing lanes. These participants said that they will ignore these irrational rules if there would not be a strict enforcement.

Q4. What offences do you often make?

Participants mentioned *the often made offences are illegal parking, crossing solid line to change lanes, and speeding on freeways or national roads*. Several participants also pointed out they sometimes drive on the wrong lane due to an inappropriate cycle time design. For example, a too long queue on the left-turn lane due to too short green time will make them lose patience and take the through going lane to make a left-turn.

Most experienced professional drivers said they were already quite familiar with the local traffic monitoring system and very few offences were recorded. According to the questionnaire, the average number of offences in the past year is 1.4 times for the professional drivers, and 1.8 times for the other participants. Every participant expressed that traffic monitoring and enforcement of the rules are directly related to the obedience of traffic rules

7.3.7 Ending questions

The ending question is to ensure that all important topics had been covered.

- How to improve driver behavior in China?
- Any other issues related to driving do you want to discuss?

Participant made the following suggestions for the Chinese driver behavior improvement:

- *Being stricter with driving testing*. More attention should be given to candidates' attitudes to traffic rules, opinions of safe driving, rather than the driving skills. In the driving license examination, more driving tests should be made on the road with real traffic surroundings.
- *Offering more education about proper and improper driver behavior and traffic rules through the news media,* such as radio broadcast, TV program, Newspaper etc. For example: traffic police enforces traffic rules in field by analyzing the traffic accidents cause, and the related responsibility distribution, etc. These measures are expected to increase the knowledge of traffic rules for all road users.
- *Introducing the traffic education system into school* as what has been done in Western countries for decades, e.g. teaching children at the age of seven the traffic rules for pedestrian and making a cycling examination at the age of 10.

7.4 Discussion and Conclusions

The private car development period in China is shorter than that in Western countries due to the motorization lag. The fraction of novice drivers with limited experience is rather large in China. Through the focus group discussions, several specific issues related to Chinese drivers' attitudes, driving manners and opinions become clear.

- *Drivers' main opinions of driving in China;*

Most of participants thought Chinese drivers' behavior is not so well, but a very limited number of participants were aware of their own aggressive driving style. They mainly ascribed Chinese drivers' special behavior to: short motorization history, high proportion of novice drivers, under-developing traffic monitoring and management systems, etc.

- *Identifying the important factors to car following;*

The important issues to 'car following' are identified as: safe distance to the preceding vehicle, and sufficient view distance. The most often mentioned factors influencing driver behavior are traffic conditions, weather, driving tasks, local traffic rule enforcement system, and personal mood. Drivers are more sensitive to the environmental factors than the personal factors. The influence of personal mood on driving style can vary among different drivers.

- *Identifying the important factors to Chinese drivers in making a decision regarding lane changing and overtaking;*

Participants expressed that traffic conditions (like congestion, long delays) have an important influence on the way they make decisions. Lane changing to a left lane is different from a movement to a right lane. To Chinese drivers, lane changing to a left lane is easier than to the right lane due to the small blind angle and less disturbances. Courtesy yielding is more likely provided for cars moving to a right lane and is not common for lane changing to a left lane. Since many drivers keep on driving on the left-most lane, overtaking has often to be done on the right side. If it is done on the left side, the overtaking car often does not move back to the original lane. The use of the right-most lane is not as common as the left-most one. Gap acceptance depends on the traffic situation and in dense traffic it is often achieved by a forced lane change.

- *What is the common way of Chinese drivers to react to signal transition?*

According to the verbal expression of the participants, the actions of the automatic gear car drivers are quite similar to those of the manual gear car drivers when they are waiting for the green signal. When the signal turns to green, professional drivers often react quicker than other drivers owing to more observations for the signals and movement on the other lanes. Most participants indicated that they concern possible conflicting traffic flows at intersections and do not dare to accelerate quickly when the signal turns to green. Many participants are neither clear about the appropriate actions to a yellow signal, nor wise to the priority rule to the remaining conflicting vehicles at a green phase. The location of the signal, the definition of stop line markings, private activities, and preceding vehicles are identified as important factors influencing drivers' reaction to signal.

- *Traffic rules implementation in China*

Most participants admitted they didn't have the habit to search for traffic signs, especially signs on the road pavement. Thus, they are quite weak in recognizing the traffic signs. Chinese drivers' knowledge of the priority rules is very limited. Most traffic rules, especially the traffic rules related to traffic signals, are considered to be important by most participants. The often made offences are illegal parking, crossing solid line to change lanes, and speeding.

Drivers' knowledge about traffic rules which they have learned in driver license courses is not reinforced by the daily driving experience, but fades away. Priority rules are not known by most drivers who have to behave carefully because they are not certain about what other drivers will do. In such traffic culture, conflicts can't be solved according to general traffic rules and the traffic efficiency becomes low in practice. This finding gives an explanation for the conclusion drawn in Chapter 4 that the saturation flow rates in Chinese cities are considerably lower than those in the Netherlands. The focus group survey presented in this Chapter revealed the underlying reasons for the special Chinese driver behavior reported in Chapter 5 and Chapter 6.

The survey results of focus groups have important implications for the improvement of driver behavior and traffic management in China:

- Stricter enforcement of the traffic rules is expected to reduce traffic rule offences and improve drive behavior.
- Driving training and testing should concentrate on the attitudes and behavior related to safe driving, rather than only on the driving skills.
- The driving test should not be considered as the final stage of driving learning and drivers should take further training or study.
- More education of traffic rules should be provided to all kind of road users to develop safe attitudes, and to reduce the likelihood of dangerous behavior.
- The installation of traffic signs and traffic signals should ensure that all relevant road users can easily identify these traffic signs and traffic signals.
- Some traffic rules, like priority rules, can be modified to be easily implemented in reality. The meaning of some traffic signs, like forbidden parking/forbidden stopping, should be modified to be clearer.

- The implementation of some traffic rules can be improved in reality, like the too low speed limits on some national roads, and too long solid line marking between two lanes.

The authorities of traffic management can exploit these survey results in driving education campaigns and traffic rule enforcement programs.

It is confirmed again that simulation models developed in Western countries should be adapted to Chinese driving conditions. This survey provides some implications for the modification of microscopic simulation models:

- Under dense traffic conditions, drivers may keep quite short space headways to prevent forced lane changing in front of them. Under free-flow conditions, drivers are inclined to keep quite large time headways, because they worry about the un-expected aberrant behavior of the preceding drivers or the adjacent drivers.
- Trucks and buses can stimulate the following vehicle to execute a lane change very quickly.
- Lane changing to a right lane requires a larger gap than to a left lane due to the larger blind angle.
- Male drivers often accelerate in lane changing, and female drivers are just the reverse. This should be confirmed by specific data collection and analysis.
- In dense traffic, drivers may start lane changing much earlier than under free-flow conditions.
- Compared with lane changing to a left lane, forced lane changing to a right-most lane can easier get cooperation from other drivers.
- Overtaking on the right side and driving on the overtaking lane for long time are quite common in urban areas in China.
- The location of the signal, the definition of stop line markings, and the category of the preceding vehicle can influence drivers' reaction to signal.

The influence of traffic conditions on driver behavior should be considered in the simulation models. Personal conditions, such as hurry, irritation and impatience, are important determinants of the driver behavior. The same driver may switch between different driving types. This can be realized by introducing a wide value distribution to the parameters in driver behavior related models. In Chapter 8, a comprehensive calibration is presented based on the data collected in Chapter 4, 5, 6 and the finding of this chapter.

Chapter 8

Microscopic Simulation Model Calibration[5]

8.1 Introduction

Micro simulation programs are often used to analyze traffic situations, assess the quality of traffic control and evaluate alternative traffic measures. If different traffic management measures are analyzed by using a simulation program, the most appropriate measure is expected to be identified in terms of the evaluation criterion, e.g. the travel time, the length of queues, etc (Dowling *et al.*, 2004; Park and Qi, 2005; Toledo *et al.*, 2003). The rationality of the conclusions drawn from such simulation studies strongly depends on the validity of the simulation. If the validity of the simulation programs is uncertain, the risk exists that the well-performing traffic management measures in simulation are not effective for the real situation. For example, saturation flow rates at signalized intersections in China are much lower than the default values in the simulation programs. If traffic engineers apply a simulation program with default saturation flow rates, the traffic designs will have insufficient capacity in bottle necks.

Fellendorf and Vortisch (2001) showed, the differences in freeway traffic between Germany and USA also make a calibration of simulation parameters necessary. This issue becomes even more critical if a simulation program developed in a Western country is to be applied in Asia where the traffic situations are quite different. For instance, the traffic composition in Asian countries differs from that in Western countries. More details have been introduced in Chapter 3. Most simulation programs have default values for model parameters. These default values are applicable if the traffic conditions and driver behavior are similar to those in the model developed country. Chapter 4 and Chapter 5 reveal that Chinese drivers differ from Dutch drivers with respect to reaction to signals, car following and lane changing, etc. Chapter 6 and Chapter 7 both indicate the necessity to adapt micro-simulation programs for the driver behavior in China.

A series of in-car tests has been conducted in Changsha, China, as described in Chapter 6. For

[5] This chapter is partly based on the paper: Calibration of a Microscopic Simulation Model for Emission Calculation (2013), by Li J., H. Van Zuylen, Y. Chen, F. Viti, I. Wilmink. *Transportation Research Part C: Emergency technology*, 31: 172–184.

36 test trips, a GPS device was installed to collect the driving information with the frequency of 1Hz. This provided abundant data for model development and calibration. In this Chapter, a study area in the city centre of Changsha is simulated by the VISSIM program. The GPS data collected from in-car tests are used to calibrate the model for four driving types which are categorized in Chapter 6. The main research questions in this chapter are:

- How to determine the calibration targets?
- How to make use of the in-car test GPS data to calibrate a simulation program?
- What are the most important parameters in VISSIM model for calibration?
- What is the difference between simulation models of four driving types?

To answer the above research questions, this chapter is structured as follows: Section 8.2 discusses important targets for simulation models calibration. Two factors, travel time distributions and saturation flow rates, are highlighted. The simulation model developing for this study is shown in Section 8.3. After that, section 8.4 discusses how to use vehicle trajectories data to calibrate desired speed distributions and desired acceleration/deceleration functions. The model validation is also introduced in section 8.4. The comparison between four driving types is presented in Section 8.5. The last section 8.6 gives a discussion of the calibration method.

8.2 Model Calibration Targets

Traffic performance in urban area includes a series of criteria, such as travel time, delay time, capacity, and queue length, etc. (Antoniou *et al*., 2014). From a model application view, these criteria form a hierarchy. Traffic flows are important and depend on route choice and OD demand (Balakrishna *et al*., 2007). Route choice depends on travel times. Travel times depend on free speeds and intersection delay. Intersection delay depends on traffic control and saturation flow rates. Saturation flow rates depend on driver behavior, acceleration and deceleration characteristics (Hirschmann and Fellendorf, 2010; Li *et al*., 2013). The basic hierarchy of simulation results and the corresponding calibration targets is shown in Figure 8.1.

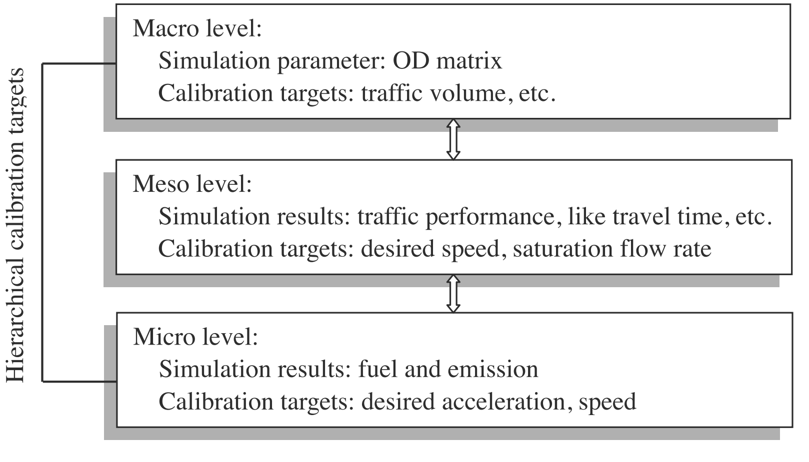


Figure 8.1 The basic hierarchy of calibration targets

As shown in Table 8.1, if the basic input parameter of a simulation model is an OD matrix, traffic volume will be a vital calibration target. If a simulation program is used to analyze the traffic capacity, delay and travel time, the calibration should at least take free speeds and saturation flow rates into account. If micro simulations are used to assess the fuel consumption and emission of pollution, the calibration has to lead to valid simulated trajectories which are relevant to drivers' acceleration and deceleration characteristics. Model calibration is a tedious and time-consuming work and the most important criteria should be chosen according to the model application. This section explains which traffic performance criteria should be used as calibration targets in order to get valid simulation model outputs.

8.2.1 Travel time distribution

Travel time distributions, directly related to travel delay distribution, are important traffic performance criteria. The calibration of microscopic traffic simulation is often done to reproduce valid link travel times. Owing to the stochastic character of queues and the stochastic effect of traffic control, travel time in urban networks has a rather large variability. Zheng (2011) has developed an analytic model for the travel time distribution. That model has been validated with travel time simulated with VISSIM and afterwards also verified with travel time distributions measured by probe cars with GPS. The travel time in urban areas consists of:

- delay at signalized intersections due to the red phase,
- delay in the upstream queue because of oversaturation (the queue did not completely clear out at the previous green phase),
- free-flow speed, and
- possible interruptions on a link, e.g. crossing pedestrians and cyclists, etc.

The consistency between the analytical model and VISSIM simulations could be made by calibrating with the following benchmarks:

- free-flow speed,
- overflow queue (queue length distribution at the end of the green phase),
- traffic control: green time, cycle time, offset, and etc.
- saturation flow rate.

Zheng (2011) has derived the delay distribution formula as follows:

$$P(w|n_i) = \alpha(n_i)\delta(w) + \sum_{k=0}^{N} \beta B(w, w_{2k+1}(n_i), w_{2k+2}(n_i)) \tag{8.1}$$

Where $P(w/n_i)$ is the probability of delay w, given the overflow queue at the start of the red phase of n_i. The Dirac delta function $\delta(w)$ is defined by

$$\delta(w) = 0, \qquad if \quad w \neq 0$$

$$\int_{-\infty}^{+\infty} f(w)\delta(w)dw = f(0)$$

$B(w, w_{2n-1}, w_{2n})$ is a box function with the property:

$$B(w, w_{2k+1}, w_{2k+2}) = \begin{cases} 1 & w_{2k+1} < w < w_{2k+2} \\ 0 & otherwise \end{cases}$$

w_{2n-1}, w_{2n} are delay boundaries determined by flow, overflow queue, signal timing (e.g., red phase, cycle time and coordination of intersections in an urban corridor). α and β are dependent on the traffic state, e.g. the flow q, overflow queue n_i, the red phase t_r and cycle time C with:

$$\alpha = \max\left(1 - \frac{t_r + \frac{(n_i+1)}{s}}{C(1-\frac{q}{s})}, 0\right), \qquad \beta = \frac{1}{C(1-\frac{q}{s})}$$

The Function (8.1) indicates that travel time distributions are determined by the traffic signals, the volumes, the (free-flow) speed and the saturation flow rate. Since the control parameters (green phase, cycle time and offset) can be directly calibrated, the crucial parameters that have to be adjusted are free-flow speed and saturation flow rates. Therefore, it can be deduced that the calibration of saturation flow rates and desired speeds are crucial for obtaining a valid simulation model in terms of the travel time distribution.

Saturation flow rates are an important characteristic for traffic flows in urban road networks. The performance of the traffic flows at signalized intersections can be determined by saturation flow rates, the flow rates and traffic control. Saturation flow rates in Chinese cities are 20~30% lower than the ones in the Netherlands due to the lack of clearance time, traffic rule offences and heterogeneous driver behavior (see Chapter 4). In most microscopic simulation models, like VISSIM, saturation flow rates are not an input parameter, but the results of the driver behavior sub models. The calibration of the parameters in these sub models should make the simulated saturation flow rates consistent with the observations in reality.

8.2.2 Speed profile and acceleration profile

Emissions and fuel consumption on urban roads are strongly determined by the details of the driving behavior. Over the past decades, some microscopic simulation models have been developed to estimate the emissions based on the characteristics of vehicles, the weather and the road, and also on the driving characteristics, such as the speed, acceleration pattern and the number of stops of a trip. This means that the speed and acceleration profiles simulated by the simulation program should be sufficiently close to the driving characteristics in reality. However, only a few studies on emissions with a microscopic simulation model paid sufficient attention to the model calibration in terms of the local driving characteristics (Li *et al.*, 2013).

A microscopic model such as VISSIM is often calibrated by comparing measured and simulated travel time and delay time (Park and Qi, 2005), travel time distributions (Zheng, 2011), or saturation flow rates (Asamer *et al.*, 2013). The same travel time and delay time can be the results of completely different trajectories (Li *et al.*, 2013). Therefore, even if a simulation program is valid in some macroscopic outcomes (such as queues and travel time), it is not guaranteed the veracity of the more detailed characteristics like speed and acceleration profiles. In order to satisfactorily predict vehicle emission, a simulation should be also valid with respect to these microscopic characteristics. There are several options to get driving data at a microscopic level (Ossen, 2008). One option is to extract trajectories from video observations by image processing technology. The video can record different vehicle movements at the same time and the trajectories extracted from video can represent various driving behaviors. But the observation period and location are both limited. Another option is to trace the paths of certain kinds of vehicle, for instance from cars probed with GPS. This kind of data collection is limited with the number of test drivers. Another limitation is that only one single vehicle is traced while the traffic surrounding is not recorded (unless all cars around are equipped with GPS).

In summary, a simulation program calibrated with the macroscopic targets (travel time, delay, traffic volume, etc) is probably not valid for some more specific traffic performance, like emission. In this case, accelerations and speed profiles derived from vehicle trajectories should be taken as the calibration targets. This chapter introduces a new method for the VISSIM model calibration based on the application of GPS data. In order to make the model suitable for both microscopic level (emission calculation) and macroscopic level (travel time), speed profiles, acceleration profiles and saturation flow rates, are selected as the calibration targets.

8.3 Simulation Model Development

In this study, 30 drivers were invited as volunteers to participate in in-car tests in Changsha. All of 36 test trips were conducted in Changsha city area (inside the second ring road) and every trip lasted for about 30 minutes. More details are presented in Chapter 6. A GPS receiver was installed in the test vehicles and could transfer the driving information to a computer once per second. The stored data include vehicle coordinates, speed, and acceleration. The accuracy of the GPS data have been tested and introduced in another paper (Li *et al.*, 2011c).

All of the in-car tests were made at off-peak hours without severe congestion and any traffic incidents. It is practically infeasible to develop 36 different models to simulate each test trip. A simplified model with one signalized intersection in Changsha city center is developed for the VISSIM program calibration. The saturation flow rates of the lanes in this intersection have been investigated and reported (Li *et al.*, 2011b). The map of this simulated intersection is shown in Figure 8.2. The route length is 1518 meter from the east to the west, and 955 meter from the south to the north boundary.

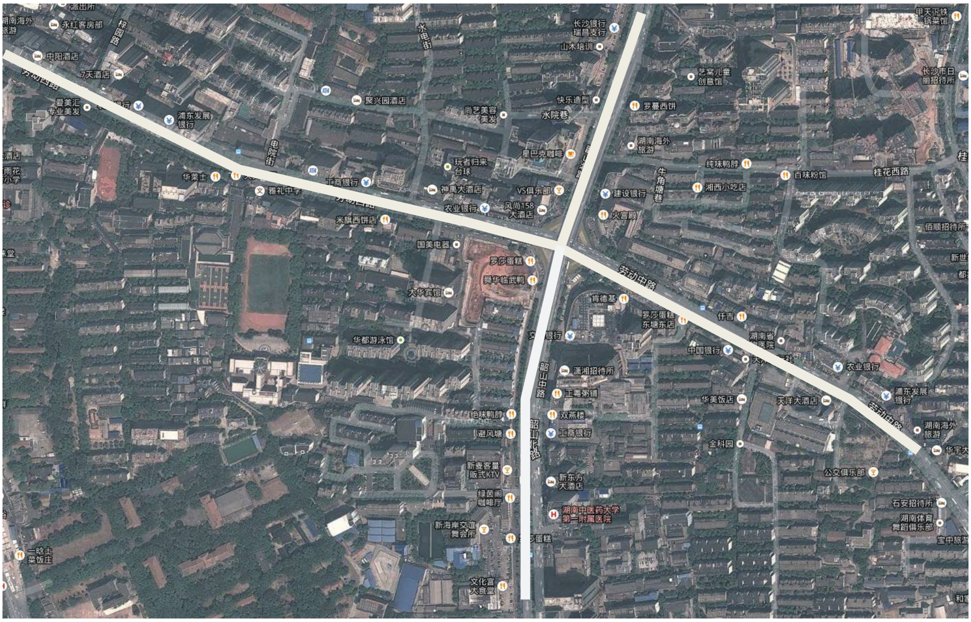


Figure 8.2 The Simulated intersection in Changsha, China (background from Google Earth)

The model calibration is conducted for four driving types which are categorized in Chapter 6. This is expected to reveal the underlying differences between different driving types. For the model development, the input data include:

- Number of stops,
- Traffic control in reality (fixed time control),
- Traffic volume, calculated from traffic density (see Chapter 6),
- The layout of modeled network (number of lanes),
- Speed limit 60km/h.

Traffic density is estimated based on a fundamental diagram, as introduced in Chapter 6. According to the fundamental diagram, traffic density is relevant to traffic volume and speed. The driving speed is strongly related to the driver behavior. The number of stops is an important index for representing the real traffic situation. Therefore, the number of stops should be the same in the simulation as in the reality for model calibration.

8.4 Microscopic Model Calibration

The VISSIM model calibration process is presented in this section. Firstly, a model sensitivity study is made to identify the most important parameters in VISSIM in terms of the calibration targets: speed and acceleration profiles and saturation flow rates. Afterwards, it is introduced that vehicle GPS trajectory data are used for desired speed and acceleration calibration. Finally, the calibration results are analyzed and validated.

8.4.1 Model sensitivity analysis

Since Li *et al*. (2013) reported that the default parameters of VISSIM do not always result in realistic trajectories, it was necessary to execute a calibration taking speed and acceleration profiles as the calibration targets. This calibration for trajectories is rather different from the usual calibration on delays, travel time and queues. Very few attempts have been made to calibrate microscopic simulation models at this level of details. Hirschmann and Fellendorf (2010) did such a calibration at a microscopic level using a few probe vehicles. Their study revealed the significant difference in detailed driving properties between different drivers. If the VISSIM program is applied with the default parameters without calibration, the discrepancy in speed and acceleration profiles between the observation and the simulation are shown in Figure 8.3 and Figure 8.4. The observed speed and acceleration are from the in-car tests conducted in Changsha, as introduce in Chapter 6.

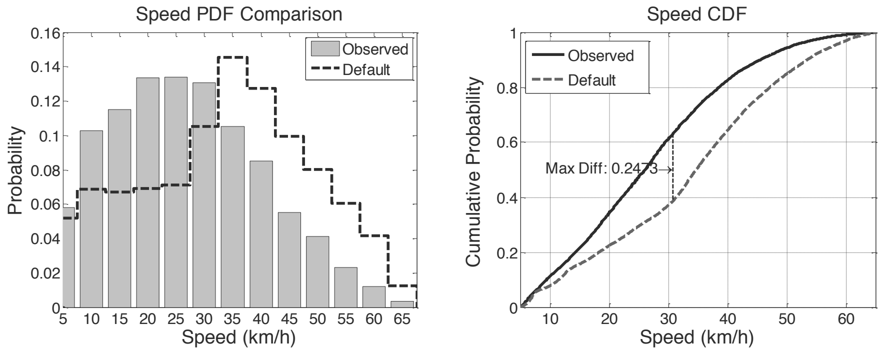


Figure 8.3 Comparison between observed and simulated (default) speed distributions

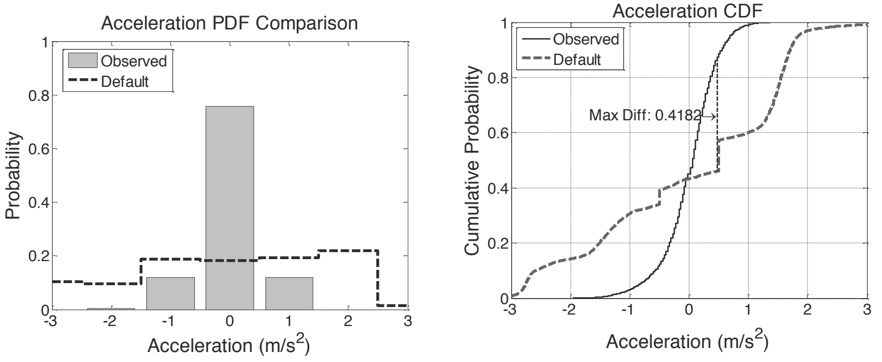


Figure 8.4 Comparison between observed and simulated (default) acceleration distributions

In order to evaluate the consistency between the observed and simulated data distributions, the Chi Square Error (X^2) is introduced as:

$$X^2 = \sum_{i=1}^{N} \left\{ (f_{i,observed} - f_{i,simulated})^2 / f_{i,observed} \right\} \tag{8.2}$$

Figure 8.3 shows a distinct discrepancy of speed and acceleration distributions between the observation and simulation. The X^2 value is 0.2895 for speed distributions and 2.6022 for acceleration respectively.

At present, commercial traffic simulation program has a general tendency that more and more parameters are involved in the simulation to catch the specific traffic characteristics and to satisfy the implementation requirements in practice. This tendency increases the number of parameters available for calibration. For example, VISSIM 5.40 has 192 parameters (Antoniou *et al*., 2014). Before conducting calibration for a traffic simulation model, a sensitivity analysis is required to answer a crucial question: which parameters among the huge set of parameters are relevant to the calibration in terms of the simulation study objectives?

Generally, the approaches to conduct a sensitivity analysis can be mainly classified into two types. The more common way is to change the relevant parameters one by one while keeping all others as the default or fixed values. It is referred to One factor at A Time (OAT). This simple 'local' method can't reveal the interaction among different parameters. In the last decades, a new approach referred as Global Sensitivity Analysis (GSA) was developed. This method constructs a relation between model inputs and outputs by running the model for a large number of times. The combination of inputs is often based on a certain framework, like a Monte Carlo framework. A result of GSA might be the sensitivity indexes that identify the importance of the parameters to the outputs (Antoniou *et al*., 2014). GSA method requires a special mode to run the model for a massive number of times.

Li *et al*. (2013) conducted a sensitivity analysis to determine the most important parameters and functions according to the influence on speeds and acceleration profiles and saturation flow rates. The OAT search procedure is applied in this sensitivity analysis. Namely, the parameters related to driving behavior were changed one by one or in groups, while the other parameters were kept constant. The interaction between parameters can only be identified by applying this procedure iteratively for different combinations of parameters. Based on the sensitive analysis results reported by Li *et al*. (2013), the most relevant parameters to the simulated distributions of speed/acceleration and saturation flow rates were confirmed as:

- The desired speed distribution,
- The desired acceleration function,
- The desired deceleration function,
- The maximum deceleration function,
- Some parameters in car following behavior model.

These parameters play a role in the Wiedeman 99 model that is used in VISSIM (Wiedeman 1991). In the next sub-sections, the model is calibrated in such a sequence: 1) the desired speeds distribution calibration based on the simulated speed profiles; 2) desired acceleration and deceleration functions based on the simulated acceleration profiles; 3) car following model calibration mainly based on the simulated saturation flow rates.

8.4.2 Desired speed distribution calibration

As explained in the previous section, the desired speed (equivalent to free speed on highways) distribution is directly related to speed, and relevant to the travel time. The observed speeds presented in Figure 8.3 are from the driving type 2, one from the four driving types categorized in Chapter 6. The 50-percentile of the observed speed is about 25 km/h, considerably lower than the simulated speed 35 km/h in VISSIM with default desired speed distribution. The desired speeds in reality should be lower than the default linear distribution shown in Figure 8.5 (left).

Since drivers have more interactions with each other at a low speed than driving at a high speed, the probability of drivers who achieve the desired speeds depends on the present speed: the higher the speed of driving, the larger the probability of achieving desired speed, and vice versa. The censoring function developed by Li *et al*. (2013) was used to deduce the desired speed distribution from observations. All of observed speeds are classified into different classes with an interval of 5km/h: 0~5km/h, 5~10km/h, 10~15km/h, etc. For every speed class, the median value is the representative, for example 32.5km/h representing speeds (30~35km/h). The censor function is based on the following assumptions:

- The percentage of speeds (< 32.5km/h) being a desired one is 0;
- The percentage of speeds (= 32.5km/h) being a desired one is p (32.5);
- The percentage of speeds ($32.5 \leq s < 67.5$ km/h) being the desired one increases linearly;
- The percentage of speeds ($\geq$ 67.5km/h) being a desired one is 100%.

The linear function can be described as:

$$\begin{aligned} &p(s) = 0 && (0 \leq s < 32.5 \text{ km/h}) \\ &p(s) = p(32.5) + \alpha\,(s\text{-}32.5) && (32.5 \leq s < 67.5 \text{ km/h}) \qquad (8.3) \\ &\alpha = (100\text{-}\,p(32.5))/35; && \end{aligned}$$

Where:

s: the median of a speed class (km/h);

$p(32.5)$: the percentage of speeds at 30~35km/h being a desired one;

$p(s)$: the percentage of speeds at a class (s) being a desired one.

The data for censoring are selected with two conditions:

- Speed > 30 km/h;
- Acceleration > 0 m/s^2.

In this linear censor function, there is only one parameter $p(32.5)$ that should be calibrated. For every observed speed class s, the speeds larger than the percentile of '100- $p(s)$' are kept as the desired speeds, and all of the other lower speeds are filtered. For example,

If $p\,(32.5) = 16$,

$\alpha = (1\text{-}\,p(32.5))/35{=}2.4$

$p(42.5) = 16 + 2.4\,(42.5\text{-}32.5){=}40$

'$p(32.5) = 16$' means that speeds larger than 84 percentile at the speed class 30~35km/h (median speed 32.5km/h) are selected as the desired speed. '$p(42.5) = 40$' indicates that speeds larger than 60 percentile at speed class 40~45km/h (median speed 42.5km/h) are selected as the desired speed. Speeds lower than the 100-$p(s)$ percentile are considered as restricted speeds and filtered out. Namely, at speed 30~35km/h, 84% of speeds are filtered; and this value is 60% at speed 40~45km/h. The parameters $p(32.5)$ is determined by minimizing the difference between the observed and simulated speed distributions. For driving type 2, $p(32.5)$ is calibrated as 0.05. Based on the censer function (8.1) calibration results, a new desired speed distribution is deduced, shown in Figure 8.5 (right). The consistency between the observed and simulated speed distributions is improved distinctly, with Chi Square Error X^2 decreasing from 0.2895 to 0.0240. Figure 8.6 shows that the cumulative probability curve of observed speed is rather close to the simulated one. The similar procedure has been applied for the desired acceleration and deceleration calibration.

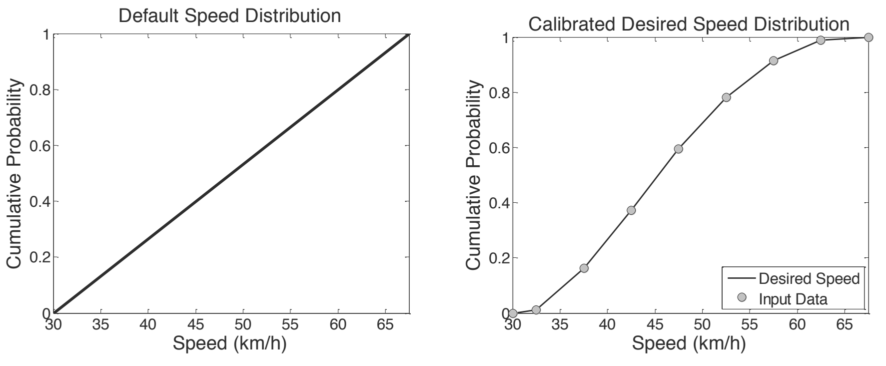


Figure 8.5 Default desired speed distribution (left); calibrated desired speed distribution (right) (calibration for driving type 2)

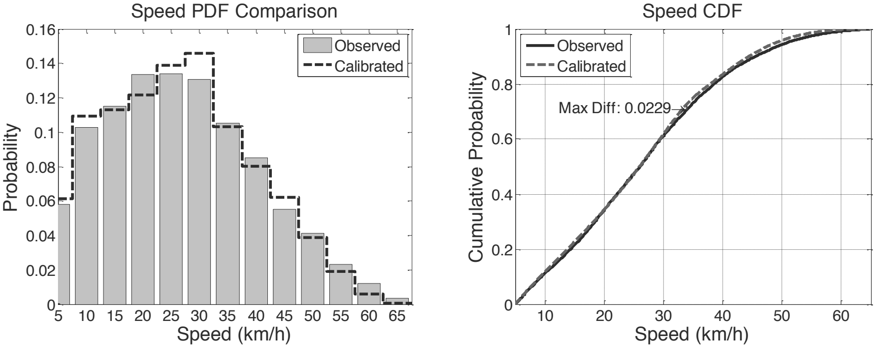


Figure 8.6 The comparison of the observed and simulated speed distribution (calibration for driving type 2)

8.4.3 Desired acceleration and deceleration function calibration

Hirschmann and Fellendorf (2010) measured trajectories from probe vehicles with high frequency GPS and deduced the acceleration characteristics for a few drivers. The results of the comparison indicated that drivers differed in acceleration behavior (Hirschmann and Fellendorf, 2010). Therefore, it will be better to identify the desired acceleration/ deceleration functions for the four driving types categorized in Chapter 6.

If the VISSIM simulation model is applied with default parameters without calibration, the discrepancy of acceleration/deceleration distributions between simulation and reality is dramatic. As shown in Figure 8.4, The Chi Square Error X^2 is 152.4242. Quite large proportions of high accelerations and high decelerations are simulated by the VISSIM model with default functions. In reality, most accelerations and decelerations are between -0.5 and 0.5m/s^2. The distinct difference in acceleration/deceleration between simulation and reality highlights the importance of calibration of functions/parameters related to acceleration/deceleration in VISSIM. There are four functions related to acceleration and deceleration:

- Maximum acceleration,
- Maximum deceleration,
- Desired acceleration,
- Desired deceleration.

In VISSIM, acceleration and deceleration are a function of the current speed. Combustion engines reach their highest acceleration at low speeds, as shown in Figure 8.7. The maximum acceleration is defined as the technically possible acceleration. Maximum deceleration is also the maximum technically possible deceleration. Desired accelerations/decelerations are used when the maximum acceleration/deceleration is not required (PTV, 2013).

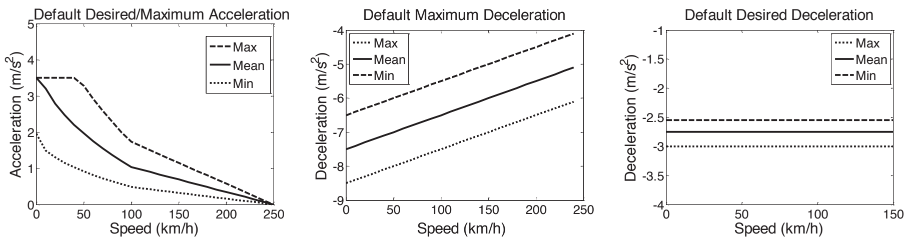


Figure 8.7 Default desired acceleration/deceleration and Maximum acceleration /deceleration function in VISSIM

Figure 8.4 shows that some decelerations larger than the maximum desired deceleration have been produced by VISSIM. This case is not found in the acceleration distribution. It indicates that maximum deceleration function can influence the simulation of deceleration even in normal driving situations. The calibration should be conducted for both the maximum deceleration and desired acceleration/deceleration functions in VISSIM.

Maximum deceleration and desired deceleration

In this study, the maximum deceleration and desired deceleration are expected to be derived from the observed deceleration. Maximum deceleration can be considered to be used in an emergency situation, which is assumed to contribute 5% of the observed decelerations. These highest 5% decelerations can be considered as the maximum deceleration distribution with the largest value, median value and lowest value, as shown in Figure 8.8 (left). The other 95% of decelerations are all classified as desired ones with the boundary: 5 percentile for largest value, 52.5 percentile for median value ((5+100)/2=52.5), and 100 percentile for the lowest value respectively. The calibrated desired deceleration function is described in Figure 8.8.

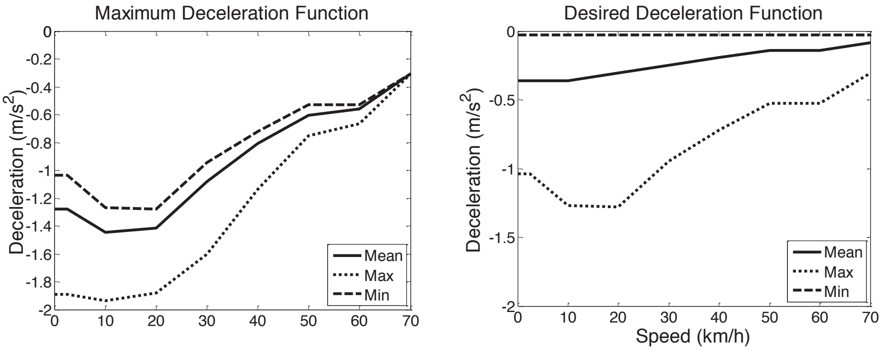


Figure 8.8 Maximum deceleration and desired deceleration calibration results (driving type 2)

The calibrated low boundary of desired decelerations is quite close to zero, much lower than the default curve. This result is more consistent with the driving in reality: drivers prefer a smooth driving condition and often only use the low deceleration in most traffic situations.

Desired acceleration

VISSIM has the desired accelerations as input parameters which can be calibrated with the similar censor method as being used for desired speed estimation. Figure 8.9 shows the cumulative distribution of the observed accelerations per speed class. Due to the stochastic characteristic of driver behavior, the largest observed acceleration can be considered as the maximum desired acceleration boundary. The critical step of desired acceleration calibration is to deduce the lowest desired acceleration boundary with the censor method. This basic assumption is that the probability to realize the desired acceleration is low at low speeds because of the interactions between vehicles. It is assumed that this probability increases linearly with the increase of speed, and is assumed to be 100% at the highest observed speed class 70 km/h. That means that there is no restriction in accelerating when driving at 70 km/h.

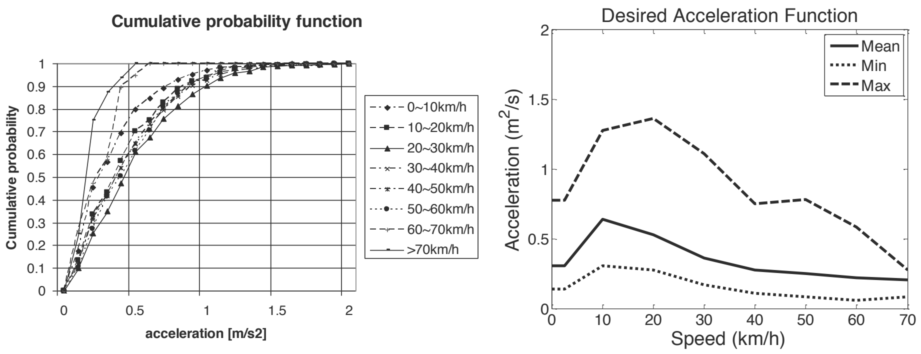


Figure 8.9 Cumulative distribution of observed accelerations per speed class (left) and calibrated desired speed function (right)

The calibrated acceleration is also a distribution with values varying between the maximum observed acceleration and '100−$p(s)$' percent of the high accelerations at speed s. The linear censor function can be described as:

$$p(s) = 0 \qquad (0 < s < 5 \text{ km/h})$$
$$p(s) = p(0) + \alpha \times s \qquad (5 \leq s < 70 \text{ km/h}) \qquad (8.4)$$
$$\alpha = (100\text{-}\ p(0))/70;$$

Where:

s: the median of a speed class (km/h);
$p(0)$: the percentage of accelerations at low speeds 0~2.5km/h being a desired one;
$p(s)$: the percentage of acceleration at a speed class (s) being desired one.

The data for censoring are selected with two conditions:

- Speed > 0 km/h;
- Acceleration >0 m/s^2.

Figure 8.9 (right) shows the calibrated desired acceleration for the driving type 2 in Changsha. It also presents the largest boundary (the 100 percentile of observations), the median values ((100+ $p(s)$)/2 percentile of observations) and the lowest boundary ($p(s)$ percentile of observations) respectively. When this calibrated acceleration function is compared with the default patterns in VISSIM Figure 8.7 (left), it is obvious that the drivers accelerate less 'aggressive' in reality. This result is consistent with the calibration done for an intersection in Rotterdam, the Netherlands (Li *et al*., 2013). After the calibration of the desired speed distribution and desired acceleration/deceleration function, and the maximum deceleration functions, the discrepancy between the observed and simulated acceleration profiles decreases significantly, as shown in Figure 8.10. The Chi square error X^2 decreases from 2.6022 to 0.0099.

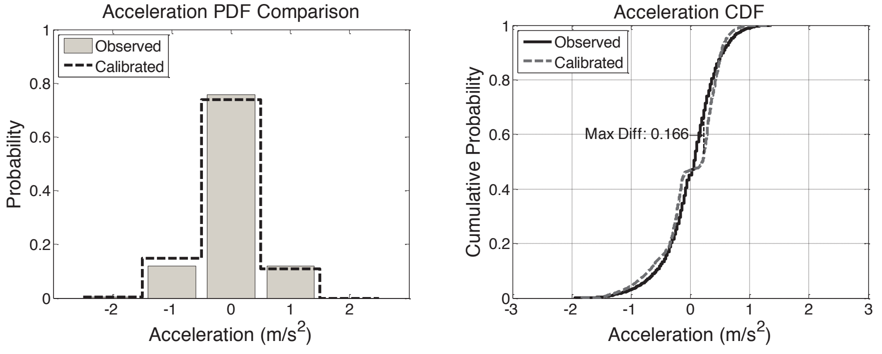


Figure 8.10 Observed and simulated acceleration distribution after calibration

The calibration of speed, deceleration and acceleration has an important influence on the simulation results, because a low desired speed and desired acceleration are expected to give a lower saturation flow rate. Therefore, the calibration of VISSIM has to be continued with an adjustment of the other parameters, especially the parameters strongly related to saturation flow rates in the car following model.

8.4.4 Calibration of saturation flow rates

If the desired speed distribution of Figure 8.5 (right) and the desired acceleration function of Figure 8.9 (right) are introduced into VISSIM without further adaptation of the car following parameters, the saturation flows becomes very low. Therefore, the parameters of the car following model have to be adapted consequently. Not all parameters that can be chosen in VISSIM are relevant for the calibration of saturation flow rate. A sensitivity analysis shows that the following models/parameters in VISSIM have a significant influence on the simulated saturation flow rate:

- Desired speed,
- Desired acceleration,
- Car following behavior,
- Vehicle length.

Since the functions and distributions related to acceleration and speed have been calibrated, and the vehicle lengths in Changsha is not significantly different from the ones in Europe, the only parameters left for further calibration are the car following model. In this VISSIM simulation model developed for Changsha, the Wiedemann 99 model is selected as the car following model. According to the sensitivity analysis made by Li *et al*. (2013), the following parameters in the Wiedemann 99 model influence saturation flow rates significantly:

- Time headway, the time headway a driver wants to keep from the predecessor (CC1),
- Following variation, the maximum deviation of the preferred following distance that a driver accepts before he reacts by accelerating (CC2),
- Threshold for entering the state ‘Following’, the time of action (deceleration) before a driver enters the safety distance with his predecessor (CC3),
- Oscillation acceleration, the actual acceleration while driving in car following (CC7),

- Acceleration from stand still (CC8).
- The definition of these parameters is given by PTV (2013).

The most important parameters for the calibration of saturation flow rate are CC1 and CC2. The other three parameters have a minor influence. The parameter CC8 could directly be found in the desired acceleration data. For the calibration of the car following parameters an iterative pair-wise optimization is done: CC1 and CC2 are correlated with each other, and are both strongly related to saturation flow rate. The calibration is conducted in a two dimensional grid search, with the saturation flow rate as target. The saturation flow rates of the simulated intersection has been investigated by Li *et al*. (2011b). As found by Asamer *et al*. (2013), there are several combinations of CC1 and CC2 that give the same saturation flow rate. CC3 and CC7 both have a certain influence on the acceleration profile. Therefore, after the calibration of saturation flow rates, CC3 and CC7 are calibrated simultaneously with the acceleration profile as target.

As used by many previous calibration studies (Antoniou *et al*., 2014), the deviation of saturation flow rates between simulation and reality should be within 5%. The saturation flow rates calibration results are show in Table 8.1.

Table 8.1 Saturation flow rates calibration results

Lane	Observed saturation (pcu/h/ln)	Simulated saturation (pcu/h/ln)	Relative error (%)
13022	1692	1694	0.12
13023	1644	1700	3.41
13082	1576	1486	-5.71
Average	1637	1627	-0.73%

Note: 1. Three representative through going lanes;
2. Saturation flow rates are calculated by the regression method, as introduced in Chapter 4.

After the calibration of CC1 and CC2, the simulated acceleration profile only changes slightly. CC3 and CC7 are calibrated pair wise to minimize Chi-square error X^2 of the acceleration distribution. Afterwards, an iterative calibration is often required to assure the calibration quality of saturation flow rate and acceleration distribution.

A final check of the whole calibration is made to confirm the output speed distribution. The results usually show that the new parameter settings found in a second iteration nearly do not change any more. The car following model final calibration results are shown in Table 8.2.

Table 8.2 Car following model calibration results

Parameters	CC1	CC2	CC3	CC7	CC8
Default	0.9	4.0	-8.0	0.25	3.5
Calibrated	0.75	2.0	-6.0	0.5	0.9

8.4.5 Model validation

The final step of model calibration process is model validation which compares simulation outputs with empirical data not used for model calibration. Model validation is to check whether the calibrated model is close enough to the traffic system in reality, especially the influence of changes in the system. Thus, a valid model should not only replicate current traffic measurements, but also can accurately predict the effects of changes in the current system.

In this study, the data set of driving type 2 has been split into two independent data samples, one for the calibration and the other one for the validation. Every data sample includes 8 test trips with the same estimated number of stops and traffic density: 45 stops per hour and 59.6 vehicles per lane per kilometer. The comparison between the simulation outputs and the observed acceleration /speed is presented in Figure 8.11. The speed Chi-square error is 0.0059 and the acceleration Chi-square error is 0.0156, which indicates that the simulation outputs are quite close to the observations.

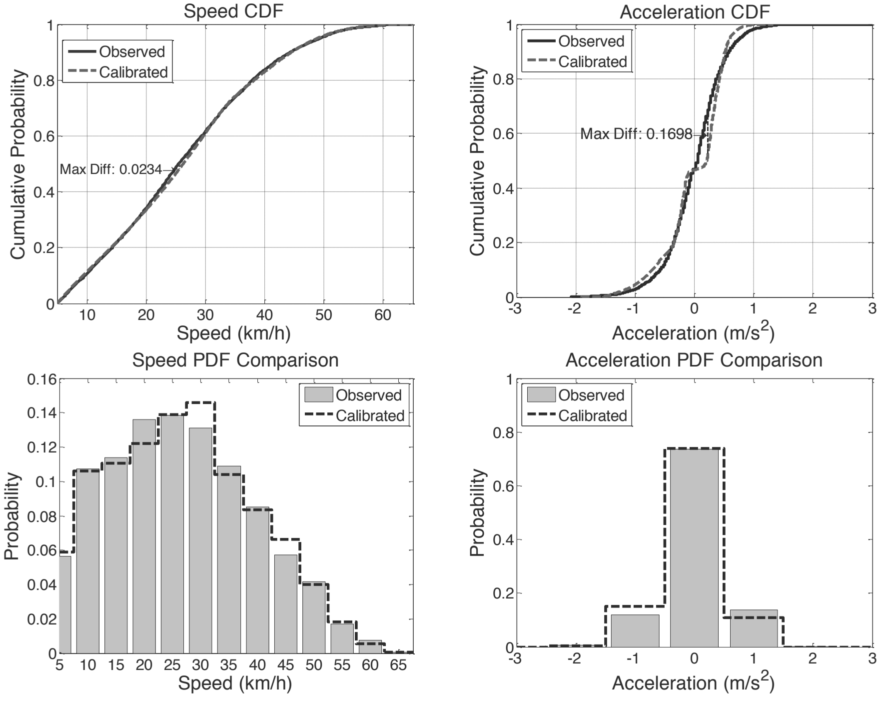


Figure 8.11 Model validation under the similar traffic conditions
Note: Number of stops per hour = 45; Traffic density = 59 vehicles /ln/km

In order to reveal the responses of the calibrated model to the changes in the traffic conditions, the 8 trips used for validation are separated into two parts: one has fewer stops with low traffic density and the other is on the contrary. The comparison between simulation outputs and empirical data under different traffic conditions is presented in Table 8.3.

Table 8.3 Comparison between simulation outputs and empirical data under different traffic conditions

Data sample	Number of stops per hour/ Traffic density (veh/ln/km)	Speed Chi-square error	Acceleration Chi-square error
Calibration (8 trips)	45/59	0.0240	0.0099
Same traffic conditions (8 trips)	45/59	0.0059	0.0156
Fewer stops (4 trips)	32/55	0.0157	0.0286
More stops (4 trips)	58/64	0.3859	0.0140

It is distinctly shown in Table 8.3 that the calibrated model can simulate drivers' acceleration behavior quite well under different traffic conditions. The simulated speed distributions are close to the observed ones in most cases, except in the high traffic density with much more stops.

8.4.6 Calibration procedure discussion

The whole model calibration process based on the censor method can be separated into five steps, as shown in Figure 8.12.

The first step is to derive the desired/maximum deceleration functions and car following model parameter CC8 from the empiric data, as described in Section 8.4.3. The second step and the third step both use the censor method to calibrate the desired distribution function. In the fourth step, the saturation flow rate calibration is conducted by a two dimensional grid search. The last step is to calibrate the other two parameters in car following model which are relevant to the output of acceleration distribution. The fourth step and the fifth step are an iteration of calibration for the car following model in VISSIM. The calibration procedure could be rather fast and efficient. However, it is not sure in beforehand whether the interrelationship between the different steps makes any iteration necessary. One issue is often doubted: *Does the calibration in the current step influence the calibration results in the previous step?*

To eliminate the suspicions of the interaction between different steps, a check has to be made by redoing the calibration starting with the parameters found in the first sequential calibration. Usually, the Chi-square error has converged after two iterations in calibration. Due to the stochastic property of VISSIM model, simulation results may be different if the random seeds in VISSIM change. When the sum of chi-square errors between observation and simulation is lower than this between simulation runs with different random seeds, the calibration can stop.

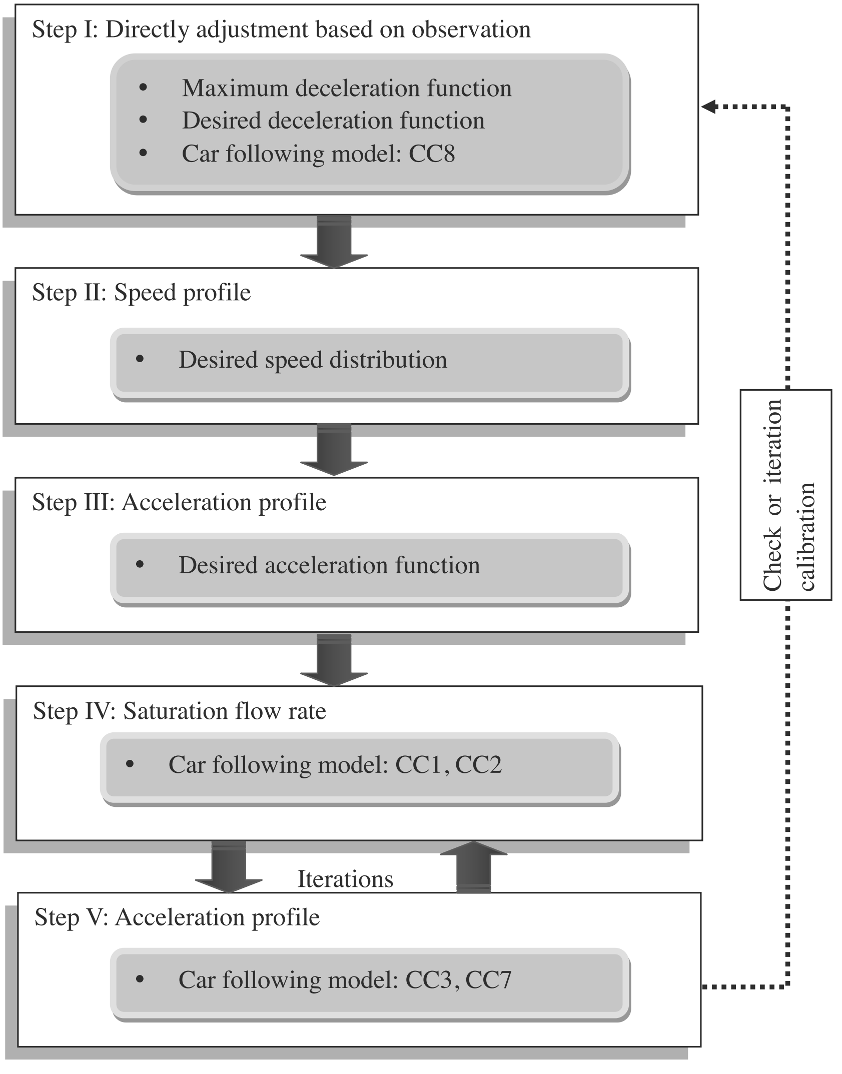


Figure 8.12 Flow chart of VISSIM model calibration

8.5 Driving Type Analysis

According to Driver Behavior Questionnaire (DBQ) and in-car test results, four driving types have been classified in Chapter 6. In this Chapter, four models are developed can calibrated for these four driving types. The configuration of the four models is the same. In order to keep the simulated traffic conditions similar to the conditions during the tests, the traffic volume and number of stops per hour are both consistent with the values estimated in Chapter 6. The difference in the number of stops per hour is achieved by adjusting the traffic control in four models. If all other parameters are kept the same, the speed and acceleration/deceleration calibration results are summarized in Table 8.4. The value of *p* is the probability (percentage) that an observed speed or acceleration at a certain low speed is a realization of the desired ones. Take driving type 1 as the example, there are only 1% of speeds of the class 32.5 km/h (i.e. 30~35km/h) falling into desired speed; 15% of accelerations at lowest speed (i.e. 0~2.5km/h) belongs to desired acceleration.

Table 8.4 Speed and acceleration/deceleration calibration results

	p		**Chi-square error**		
	Speed	**Acceleration**	**Speed**	**Acceleration**	**Sum**
Type 1	1%	15%	0.0285	0.0866	0.1151
Type 2	5%	40%	0.0100	0.0126	**0.0226**
Type 3	34%	7%	0.0678	0.0476	0.1153
Type 4	5%	25%	0.0595	0.0501	0.1096

Note: Low speed for desired speed calibration is 30~35km/h, for desired acceleration calibration is 0~2.5km/h.

Following the same calibration process, driving type 2 is calibrated best in terms of the smallest Chi-square errors. Compared with the other three driving types, driving type 2 is the most conservative driving style. This indicates that the conservative driving style is closer to the modeled driving style in VISSIM than the more aggressive and irregular driving styles. After calibration, the desired speed distributions of four driving types are shown in Figure 8.13. Driving type 2 and type 4 both have quite low desired speed and quite similar desired speed distributions. Driving type 3 has much higher desired speed distribution than the other three types.

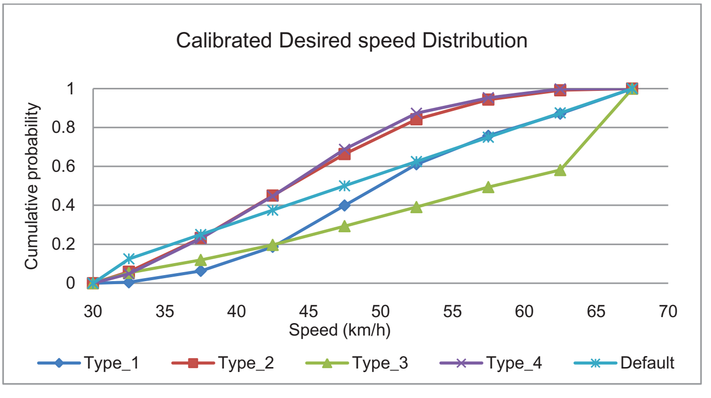


Figure 8.13 Desired speed distributions of four driving types

In VISSIM, the desired acceleration/deceleration is a function of speed. At a certain speed, the simulated driver gets a desired acceleration/deceleration from a normal distribution with maximum and minimum values. The calibrated desired acceleration and deceleration functions are shown in Figure 8.14, Figure 8.15, and Figure 8.16. All default curves of acceleration and deceleration have much higher acceleration and deceleration, and distinctly deviate from the calibrated ones. The difference of four driving types is clearly shown in the maximum desired acceleration/deceleration curves. The median and minimum curves of acceleration and deceleration of four driving types are quite close to each other.

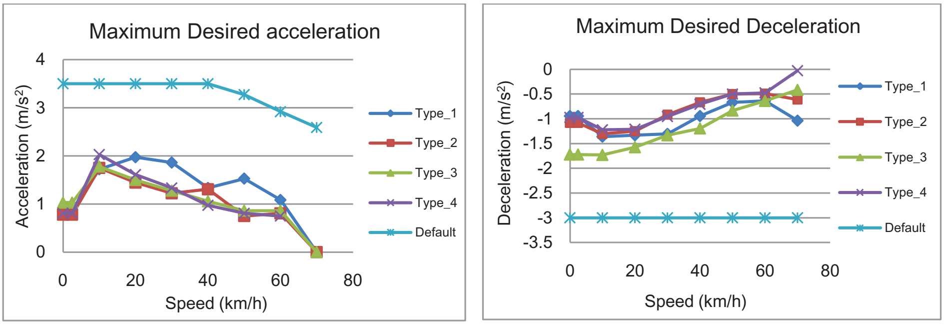


Figure 8.14 Maximum desired acceleration and deceleration for four driving types

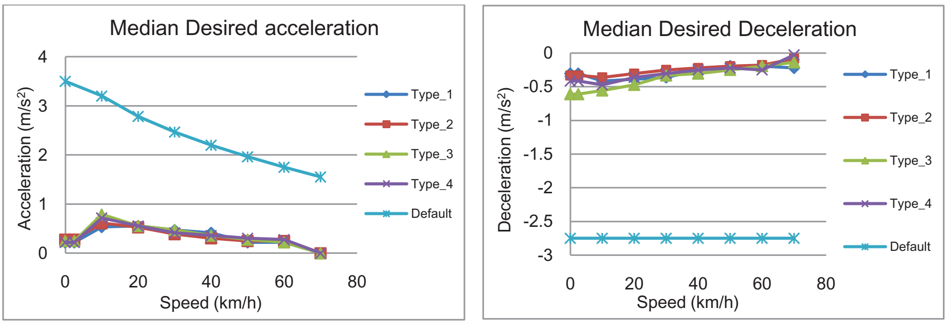


Figure 8.15 Median desired acceleration and deceleration for four driving types

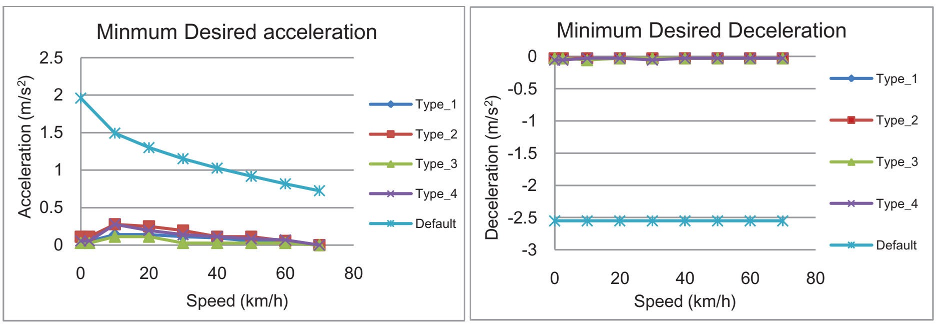


Figure 8.16 Minimum desired acceleration and deceleration for four driving types

The comparison between four driving types is mainly based on the desired speed and maximum desired acceleration/deceleration, as shown in Table 8.5. Most of the comparison between the driving types are consistent with the conclusions made in Chapter 6. A discrepancy exists in the desired speed of driving type 3 and type 4. For driving type 4, many high speeds were recorded and this type is characterized as 'speeding' in Chapter 6. In the model calibration, the number of stops has been considered. *The calibrated desired speed distributions reveal that driving type 3, not type 4, has the highest desired speed*. Apparently the observed speeds cannot be directly used to distinguish the driving types. The discrepancy between observed behavior and calibrated desired behavior indicates that driver behavior is influenced by traffic conditions. During model development and model calibration, the data collected in reality should be carefully used because of the underlying correlation between different parameters.

Table 8.5 Comparison of driving types based on calibrated simulation models

Type	Number	Description	Note
1	10	High desired speed, high desired acceleration, high desired deceleration at high speed	Aggressive, male, unsteady
2	16	Low desired speed, low desired acceleration, low desired deceleration	Conservative, female, novice
3	5	Very high desired speed, low desired acceleration, high desired deceleration,	Professional, speeding
4	5	Low desired speed, high desired acceleration at low speed, low desired deceleration	Experienced, smooth-going

The calibration method introduced in this chapter is not very complicated if the specific data (acceleration, speed, etc) are available. The category of different driving types is expected to be useful in model calibration in the future. After categorizing several representative driving types for a city or region, the traffic model calibration can mainly focus on adjusting the proportion of different driving types and most of the other parameters for each type can adopt the prior-calibrated values. This will simplify the calibration work; at the same time, the outputs of speed and acceleration will be consistent with the reality.

8.6 Discussion and Conclusions

Drivers in a Chinese city behave differently from drivers in Europe. In order to simulate traffic for China in a valid way, one has to calibrate the simulation program. This chapter starts with the analysis of the choice of calibration targets, and then develops a new method to calibrate the simulation model (VISSIM) based on GPS data from test drives. All in-car test data were collected in Changsha, China. Despite that driver behavior in Changsha cannot represent that in all cities across China, the calibration method presented in this chapter can be applied in every city, especially in cities where probe vehicles with GPS drive around. The data collection frequency possibly varies due to the use of different equipments and the influence on data quality should be checked. The main research objectives achieved in this chapter are:

- *To demonstrate the choice of calibration targets*

The calibration targets of a micro traffic model can be separated into several hierarchies: traffic flows, travel time, saturation flow rates, speed distributions and acceleration distributions, etc. The targets for the calibration of a simulation model should depend on the application of the simulation. Speed profile and saturation flow rates are important targets for calibration in most cases, while acceleration distribution is especially relevant if the vehicle emissions are simulated.

- *To develop an effective method for model calibration with GPS data*

A censor method was developed to derive desired speed and acceleration functions from the observations. It is assumed that the observed low speeds and accelerations at low speeds have a low probability of being desired values. Lower speeds represent situations where vehicles experience more restrictions due to the vehicles in front or to traffic control. At higher speeds, drivers have a higher probability to achieve their desired speed or acceleration. Based on these hypotheses, a linear censor function with only one variable is used for the calibration of desired speed and acceleration functions. The calibration shows that the acceleration and deceleration patterns derived from the observations have much lower values than those in the default settings of VISSIM. Also the desired speeds distribution curve is significantly different from the default straight line.

Starting the calibration process by calibrating the desired speed and acceleration/deceleration from the observations avoids the multi dimensional search process which takes much computation time and still can't ensure the consistency of speed and acceleration distribution. The approach described in this chapter follows a step-wise calibration process: first calibrating the speed distribution, then calibrating the acceleration and deceleration functions, and finally the car following model parameters. The iteration shows that this calibration process is quite robust.

As the final step of the calibration process, the model validation is undertaken to check to what extent the model replicates the reality. The results indicate that the calibrated model can simulate drivers' acceleration behavior quite well under different traffic conditions. The simulated speed distributions are close to the observed ones in most cases, except in the high traffic density with many stops.

- *To identify the most important parameters to the model calibration in VISSIM*

If the speed and acceleration profiles and saturation flow rates are selected as the calibration targets, the most important parameters revealed by a sensitive analysis are desired speed distribution, desired acceleration/deceleration functions, and some parameters in the car following model.

- *To reveal the difference in driver behavior between four driving types*

Four driving types have been calibrated individually. Distinct differences are found in desired speed and maximum desired acceleration/deceleration. The characteristics of different driving types are quite consistent with the conclusion made in Chapter 6. The category of driving type is expected to be useful in model calibration in the future. Then the calibration work can be simplified to determine the proportion of every driving type.

It is important to realize that traffic simulations have a limited validity. The model itself cannot take into account all kinds of drivers and all relevant factors. Furthermore, the stochastic character of the traffic process makes it unfeasible to get a full consistency between observations and simulation for all traffic characteristics. If VISSIM runs with different random seeds, the simulation results can be different at a detailed level. For example, when a Chi square test or Kolmogorov Smirnov (KS) test is applied, the simulated speed and acceleration distributions of two simulations with different random seeds are often significantly different. The calibration is not expected to achieve the level that the acceleration/speed distributions from the simulation are exactly the same as the observed ones. Statistic tests like the Chi square or KS test, which are suitable to assess the quality of calibration for macroscopic characteristics, e.g. travel time distribution, seems to be too strict to evaluate the calibration on microscopic characteristics, i.e. speed and acceleration distributions. Therefore, in this study, the best parameter setting is determined by the minimum Chi-square error which represents the difference between the observed and simulated speed/acceleration distribution.

In Chapter 6, four driving types are distinguished in terms of the Driver Behavior Questionnaire survey and in-car test results. Different driving types have different recordings of offences and accidents, which is strongly associated with traffic safety. Every driving type has unique results in the simulation model calibration, as revealed in this chapter. One interesting question related to traffic performance is: which driving type is more effective in practical driving? Further study on driving type is expected to give the appropriate answers. Driving training and education systems should be reformed to help drivers develop better driver behavior. Furthermore, traffic capacity and traffic safety both can benefit from the improvement of driver behavior.

Chapter 9

Conclusions and Future Research

This dissertation focuses on the characteristics of Chinese driver behavior and the consequent influence on traffic performance. As a reference, Dutch drivers are also studied. This final chapter starts with the general results of the research presented in this dissertation. It is followed with an extensive discussion of the findings from every survey. Finally, some recommendations for further research are formulated.

9.1 Conclusions

In this section, the general contributions are summarized for the research presented in this dissertation, following with the logical relation among these research results. Afterwards, the main findings from every part of research are integrated and presented.

9.1.1 General contributions

This dissertation presents a study of driver behavior in Chinese cities, in comparison with Dutch drivers'. After looking back to the research objectives and research questions presented in Chapter 1, the main contributions are summarized as:

- It reveals the national characteristics of driver behavior in China, with Dutch driving behavior as a basis of comparison;
- It reveals the factors which can significantly influence driver behavior;
- It identifies the influence of driver behavior on traffic performance;
- It develops a new method to classify driver behavior based on self-reported behavior and in-car tests;
- It explores a feasible way to calibrate the present microscopic simulation models based on local driver behavior;
- It provides abundant information for simulation model modification and improvement.

The research results obtained from this dissertation can be separated into three levels, as shown in Figure 9.1:

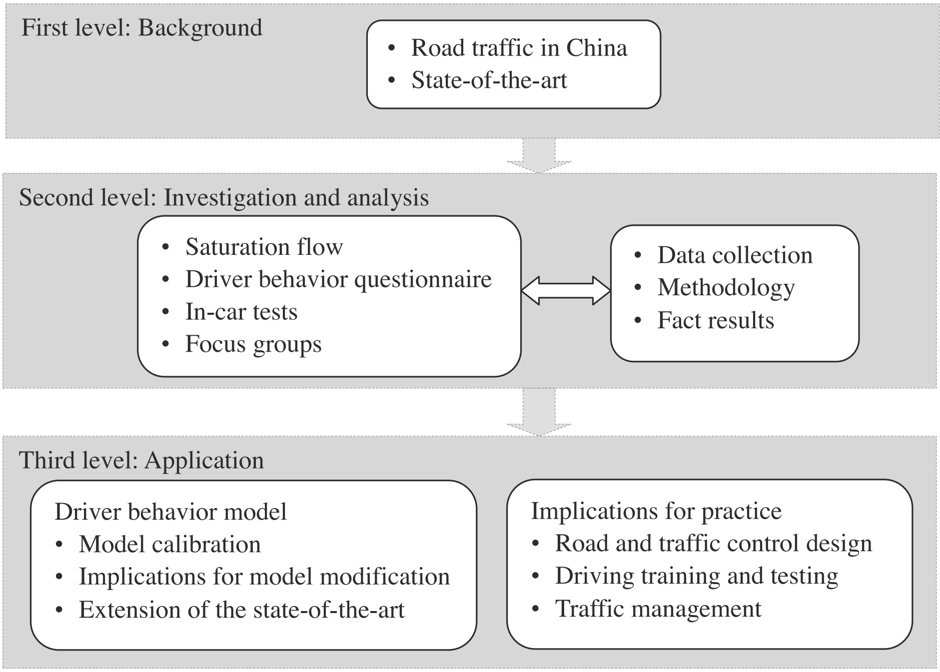


Figure 9.1 Logical relation of research results

The first level of the research results consists of the conclusions from an overview of road traffic in China and a literature review of driver behavior. The special transportation development stage together with the gap in literature inspires a comprehensive survey of driver behavior in China. In order to reveal the difference in driver behavior between China and developed countries, the Netherlands is selected for the comparative study. The surveys conducted in this study include saturation flow investigation, Driver Behavior Questionnaire (DBQ), in-car tests and focus groups. These surveys together with the data collection, research methodology and analysis results constitute the second level of the research results. The research results of the second level can be applied in microscopic model calibration and modification, extension of the state-of-the-art, and also have implications for practice.

9.1.2 Conclusions from research background

An overview of road traffic in China is presented in Chapter 2. China is the second largest vehicle country and the largest vehicle market in the world. However, in 2009 the passenger car ownership was 34.5 cars per 1,000 people, which was still at a low level compared with the average of 124.3 over the world. Due to the constant increase of new cars and novice drivers, the effect of novice drivers with limited driving experience on the traffic performance will continue for many years. Offences against traffic rules are common in China, and have become a significant inducement to traffic accidents which are an important cause for congestion in urban areas.

Chinese socio-economic conditions, traffic development status, and driving license distribution are all different from those in North America and Western Europe. This special context should be linked with the research on Chinese driver behavior. A literature review of driver behavior (Chapter 3) reveals that there are several gaps in the existing scientific publications in this field:

- Not all national characteristics of driver behavior were specificly addressed by international comparative studies. The previous international comparative studies of driver behavior mainly focused on the relationship between driver behavior and traffic accidents involvement.
- The influence of driver behavior, especially aberrant behavior, on traffic performance was not distinctly demonstrated.
- Very limited efforts were made for calibrating microscopic models based on national driver behavior features.
- It was not satisfactorily explained in the literature that the influence of culture and customs on the development of driver behavior

In order to fill in these knowledge gaps, a series of surveys were carried out in this study. The detailed procedures and results are presented in Chapter 4~7.

9.1.3 Conclusions from investigations and the analysis

Comprehensive and thorough surveys relevant to driver behavior have been conducted in this study. Comparative study of saturation flow at signalized intersections between China and the Netherlands revealed the difference in traffic performance in these two countries. Irregular driver behavior was identified as one important cause for the low saturation flow rates in China. In order to get an insight into the difference in driver behavior, an online DBQ survey was carried out both in China and the Netherlands. Since DBQ only reflects the self-reported driver behavior, in-car tests were carried out to verify the research results obtained by DBQ survey. Afterwards, focus group sessions were organized to reveal drivers' opinion of driving in China. A summary of the surveys conducted in this study is presented in Table 9.1. Some important conclusions drawn from these surveys are specified as follows:

1. Comparative study of saturation flow

Comparative study of saturation flow was carried out between China and the Netherlands. The most interesting findings are highlighted:

- Generally, the saturation flow rates in Chinese cities were 20–30% less than those in the Dutch cities, and also lower than the 'standard' saturation flow rates calculated according to the American Highway Capacity Manual formula. The start lags measured on Chinese lanes were much higher than the Netherlands values, even beyond 8s on some lanes. The number of vehicles influenced by the start lag in China varied between 4 and 6, which was also larger than what people expected before.
- The average time headways of saturation flow in China were 20-30% longer than those in the Netherlands, with much larger standard deviations. The large standard deviations of the time headways reflect the heterogeneous driver behavior in China.

Table 9.1 Summary of the surveys conducted in this study

Survey	Data collection	Methodology	Fact results
Saturation flow	• 4 intersections in 3 Chinese cities • 4 intersections in 2 Dutch cities • Movie observation	• Regression method, HCM formula • Saturation flow rate • Time headway • Start lag	• Chinese intersections are characterized with low saturation flow rates and large start lags. • Chinese drivers behave quite heterogeneously. • Traffic rule offences and the insufficient clearance time are identified as the main causes for the low saturation flow rates at Chinese intersections. • Improving the regression method to calculate the saturation flow rate.
DBQ	• Online DBQ • 215 Chinese respondents • 172 Dutch respondents	• DBQ aggressive score • Factor analysis • Nonparametric test	• Chinese respondents committed more offences and are involved in more accidents than the Dutch counterparts. • Chinese respondents' driving behavior is more aggressive and heterogeneous than the Dutch counterparts. • Factor analysis indicates that aggressive score is correlated with self/others estimated driving style in both two countries. • The implement of priority rules by the respondents in two countries are rather different.
In-car tests	• 30 participants • 36 test trips • In Changsha, China • 1 GPS device • Movies made by 3 cameras	• Factor analysis • Nonparametric test • Classifying driving type • Verifying DBQ answers	• Verifying part of the DBQ answers. • DBQ scores are validated to effectively represent the driving style in reality. • Revealing the factors which can influence driver behavior in reality. • Four driving types have been classified according to factor analysis results. • Establishing a solid foundation for of simulation program calibration. • Preliminary study of the reliability of driver behavior
Focus group	• 35 participants • 6 2-hour sessions • In Changsha, China • Movie observation • Survey tables	• Discussion	• Revealing participants' opinion about driving in China. • Identifying the important factors which can influence drivers' decision in driving. • Finding out the reasons for poor implementation of priority rules and some aberrant driver behaviors in China. • Disclosing participants' attitudes to traffic rules. • Confirming some conclusions drawn in previous surveys, like the hesitation in reacting to green signal

- Traffic offences and the remaining of conflicting vehicles both disturb the traffic flow in the protected green phase. The lack of clearance time increases the start lag, especially when there are more than three lanes suffering from the conflicting vehicles. The introduction of buffer space can increase the saturation flow rates for the left-turn traffic, but it is also a potential risk to traffic safety.
- The influence of aberrant driver behavior and conflicting vehicles on traffic performance was estimated and defined as two additional parameters added into the original regression function.

2. Comparative study of DBQ

Several important conclusions are drawn from this comparative study of DBQ between China and the Netherlands:

- According to the DBQ survey, Chinese respondents committed more offences and were involved in more accidents than the Dutch counterparts. The results of comparative study indicate that Chinese drivers underestimate their aggressiveness.
- DBQ aggressive score is introduced to evaluate driving style in terms of their answers to the questions related driver behavior. Chinese respondents got higher scores and also had remarkably larger variation in most DBQ items than Dutch counterparts.
- Most Chinese respondents did not fully understand the priority rules in driving and did not have the habit to search traffic signs in practice.

3. In-car tests in China

In-car tests were conducted for 30 drivers who totally finished 36 test trips in Changsha city, China. Every test trip lasted for about half an hour with the data collected from three cameras, one GPS device and the DBQ survey. Some important conclusions have been drawn:

- Most of the answers in DBQ were consistent with the actual driving behavior. Some driver behaviors in DBQ could not be verified due to the limitations of the videos, like the short observation time.
- Participants with a higher DBQ aggressive score had a more unsteady driving style and a more aggressive driving strategy, because they accelerated/decelerated more rapidly, changed lanes more frequently, spent more time on the left-most lane, and made more aberrant lane changes.
- Acceleration at low speeds and deceleration at high speeds provided the great separation between driving types. Different test trips made by the same drivers mostly belong to the same driving type. The plausible reason is that driver behavior is stable when the traffic situations and driving purposes do not vary too much.
- The correlation between traffic density and driver behavior indicates that the dense traffic constrains drivers' acceleration and limits lane changing possibilities, and drivers have a low probability to achieve their desired acceleration and desired speed.
- Gender was found to be significantly relevant to driver behavior. The links between driving styles and driver occupancy (professional vs. non-professional) and vehicle gear types (automatic vs. manual) were relatively weak. The sequence of DBQ and in-car test

(DBQ is prior to the test or the reverse) did not have an significant influence on the driving behavior.

4. Focus group sessions in China

Through the discussion carried out in six 2-hour focus group sessions, several specific issues related to Chinese driver behavior are specifically addressed.

- Most of participants thought Chinese drivers' behavior is not so well, but a very limited number of participants were aware of the aggressiveness in their driving. They ascribed Chinese drivers' special behavior mainly to: short motorization history, high proportion of novice drivers, under-developed traffic monitoring and management systems, etc.
- The most often mentioned factors influencing driver behavior are traffic conditions, weather, driving tasks, local traffic rule enforcement system, and personal mood. Drivers are more sensitive to the environmental factors than to the personal factors. The influence of personal mood on the driving style can vary among different drivers.
- Lane changing to a left lane is different from a movement to a right lane due to the different blind angles and disturbances. Courtesy yielding is more likely provided for cars moving to the right lane and is not common for lane changing to a left lane. The use of the right-most lane is not as common as the left-most one.
- Participants ascribed the low accelerations at intersection to the conflicting traffic. Most participants were neither clear about the appropriate reaction to the yellow light, nor fully understood the priority rules in practice. Participants' knowledge about traffic rules, especially priority rules, is not reinforced by the daily driving experience, but fades away. Participants gave some causes to explain these phenomena.

9.1.4 Conclusions from the investigation result applications

The application of the investigation results can be separated into two parts: driver behavior model and practical work.

1. Driver behavior model

<u>Model calibration:</u>

A microscopic simulation program (VISSIM) is calibrated with the GPS data collected by in-car tests in Changsha. The targets for the calibration are realistic speed, acceleration and deceleration distribution, saturation flow rates.

- The speed and acceleration profiles deduced from GPS data recorded in actual driving are significantly different from those produced by a simulation model with default parameter settings.
- The sensitivity tests reveal what parameters in the microscopic simulation model are strongly related to speed and acceleration simulation results.
- The observed accelerations could not directly be used to determine the desired acceleration, because when the vehicle is in car following status, the driver often cannot execute the desired acceleration.
- The desired acceleration and decelerations in VISSIM were calibrated using the censored

observations, which resulted in realistic simulated acceleration and speed patterns.

- GPS probe vehicles are be a convenient data source which can reveal different driver behavior of the same driver in different traffic situations.

Implications for model modification

- Parts of the national driver behavior characteristics have been calibrated in the microscopic model. Calibrating simulation model adequately for the driver behavior in China is also beneficial to the application of simulation models in other developing countries.
- The model calibration presented in this dissertation reveals that simulation programs have limitations in some of the driver behavior features. For example, the instability of driver behavior is difficult to be reproduced fully, because driver behavior can be represented quite differently with the change of personal status and external traffic conditions.
- A solid foundation for the calibration of simulation programs has been established. Microscopic simulation models can be calibrated based on the driving characteristics of different driving styles. Some additional information, such as the use of the left-most lane, overtaking on the right side, can also be adopted for the simulation model modification.

Extension of the state-of-the-art

The study presented in this dissertation fills in some gaps in the state-of-the-art.

- The national characteristics of driver behavior in China are specificly addressed by the comprehensive surveys.
- This study identifies the influence of culture and custom on the development of driver behavior. Some important implications are made for driver behavior improvement.
- The influence of driver behavior, especially aberrant behavior, on traffic performance is distinctly demonstrated.
- This study develops a new method to classify driver behavior and the consequent application for driver behavior model calibration.

2. Implications for practice

The study results presented in this dissertation have important implications for the improvement of road design, driver behavior and traffic management in China.

Road and traffic control design

- The investigation results show that capacity manuals and design standards developed in Western countries have to be adapted to Chinese conditions.
- Lots of opportunities have been found to improve the traffic control at intersections in China. The installation of traffic signs and traffic signals should ensure that all relevant road users can easily identify these signs. Sufficient clearance time should be introduced to the traffic control design to reduce the start lag and to enhance traffic safety.
- Road and intersection configuration design can be modified to optimize the space utilization of intersections. The lane markings should be improved to reduce aberrant driver behavior.

Driving training and testing

- Driving training and testing should give more attention to safe driving behavior, rather than the driving skills. Irregular driver behavior disturbs traffic flow distinctly. The investigation results show Chinese drivers are always uncertain and hesitant while driving, which makes the traffic flows inefficient.
- The knowledge of traffic rules, especially priority rules, should be emphasized. At present, priority rules are not fully understood by most drivers and conflicts cannot be efficiently solved by general traffic rules.
- Additional training and education of driving are proposed to be taken after drivers get a license. The driving test should not be considered as the final stage of driving learning and drivers should take further training or education.

Traffic management

- Strict enforcement of the traffic rules is expected to reduce traffic rule offences and improve driver behavior.
- Some traffic rules, like priority rules, can be modified so that they can be easily implemented in reality. The meaning of some traffic signs, like forbidden parking/forbidden stopping, should be modified to be clearer. The implementation of some traffic rules can be improved in reality, like the too low speed limits on some national roads.
- More education of traffic rule should be provided to all road users to develop safe attitudes, and to reduce the likelihood of dangerous behavior. For example, China can introduce the traffic education system into school as what have done in Western countries.
- The authorities of traffic management can exploit these survey results in traffic safety education campaigns and traffic rules enforcement programs.
- The causes identified for the inefficient traffic performance and the improper driver behavior in China can become a significant reference for other developing countries.

9.2 Recommendations for Further Research

According to the research presented in this dissertation, the recommendations for future research are formulated from three aspects: further improvement for driver behavior models, challenges to study of traffic safety, and new comparative study of transportation policy.

9.2.1 Further improvement for driver behavior models

The study presented in this dissertation mainly focuses on driver behavior in urban areas. Several topics in the same research area can be specified further in the future study.

- *Specific study of lane changing behavior*

Based on the data collected in this study, a further study can be made for drivers' lane changing behavior. Lane changing behavior can be classified into several types according to the speed, acceleration, lane changing duration and the objective of lane changing. The gap acceptance is an important factor to lane changing, but cannot be measured from the data-set in this study. The further study of lane changing behavior should collect new data which can be used to measure gap acceptance, for example trajectory data extracted by image processing technology. The characteristics of every lane changing type can be used for microscopic simulation models calibration.

- *Modeling driver behavior under dense traffic conditions or in a bottleneck*

The actual driver behavior that can be observed in Chinese cities has the tendency to maximize individual benefits in driving and does not care about the negative influence on the whole traffic conditions: gridlock of queues, low utilization of the capacity of bottlenecks (bridges and intersections) and a high rate of (small) accidents. This ‘pushing’ behavior results in the large drop of capacity in dense traffic and quick deterioration of traffic conditions.

The study in this dissertation indicates that Chinese driver behavior is influenced by the traffic conditions and follows different rules in dense traffic, which cannot be described by the general models for gap acceptance, lane changing and car following. A new lane changing behavior model is proposed to integrate gap acceptance and gap enforcement mechanism. Based on the gap enforcement mechanism, drivers change lanes without a real gap and they enforce drivers on the other lane to slow down or even to stop to give way. The new model will enrich the present state-of-the-art of driver behavior model and reveal the cause for low capacity utilization on bottlenecks. It will benefit driver education and traffic management on bottleneck.

9.2.2 Challenges to traffic safety study

The survey results in the dissertation reveal that Chinese driver behavior is characterized with: aggressive driving style, frequent irregular driver behavior, and high rate of offences. Evidence found in this study shows that driver behavior is strongly correlated to the traffic condition and has influence on the traffic performance. Even though extensive traffic safety related study can be found in the literature review, there are still several topics that can be specified further in the future:

- *The influence of driver behavior reliability on traffic safety*

The overview of road traffic in China illustrates that the traffic fatality is still quite high compared with developed countries. The analysis of traffic accident cause shows that driver behavior plays a critical role in traffic safety. In-car tests indicate that driver behavior is quite stable in the similar traffic situation with the same driving task. The focus group discussion reveals that traffic conditions impact driver behavior significantly. Good road design and traffic management should ensure the stability of driver behavior to a certain extent. Traffic safety study based on the stability of driver behavior, traffic management, and road geometry characteristics is expected to reveal the complex correlation among these factors. The research results will be significant to the improvement of traffic safety.

- *Calibrating traffic safety evaluation models for urban roads based on Chinese driver behavior*

According to the Highway Safety Manual (HSM) in United States, the traffic safety can be evaluated by various crash prediction models. From 2004, traffic safety on freeways and first class highways in China is required to be evaluated based on the ‘Guidelines for Safety Audit of Highway'. Some of the crash prediction models in these two countries are quite similar to each other. Until now, there is not a national guideline for the safety audit of urban roads. Traffic safety in urban areas will benefit from the safety audit of urban roads. This study can start from the calibration of crash predication models for intersections where most conflict flows appear.

9.2.3 Challenges to transport policy study

It has been illustrated in Chapter 4 that urban road capacity can be improved by 20~30% after conducting a series of measures. Even though the traffic performance can benefit from the enhancement of road capacity, it still cannot solve the traffic problems in a sustainable way. Since the vehicle ownership increases with the yearly rate larger than 10% in China, the road capacity improvement just counteracts the growth of traffic for 2 to 3years (see Chapter 2). The discrepancy between traffic supply and traffic demand has to be solved from transport policy aspect. One interesting research topics are recommended for the future study.

- *Interaction between transport measures and public attitudes*

Given the fact that Chinese people are different in attitudes, habits and culture, it will be desirable to know the possible attitudes to certain transport measures which have been shown to be effective in Western countries. Transport measures are designed based on the national social economical conditions and transport development stage, but these measures can also be adapted to people's reactions and attitudes. For example, the government makes the transport policy to give priority to develop public transport with a series of measures: exclusive bus lane, priority signal for buses, high parking fare for private cars, high tax for selling private cars, etc. These measures are all not new and have been implemented in several countries before. To a developing country, it will be important to identify what the effect of a certain measure will be on the national transport development, and what people's attitudes to these measures will be in the beginning. It is likely that policies that are effective in a Western country will not work well in China and vice versa. Comprehensive study of the interaction between transport measures and public attitudes will provide a very important reference to the design of transport measures, and predict the effect of the measures on transport development.

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Appendix A

Characteristics of Driver Behavior in Urban Areas

Note: In this appendix, the typical characteristics of driver behavior in urban areas will be introduced. It can be considered as an addition to the literature review presented in Chapter 3.

Signalized intersections are critical nodes in an urban traffic network. The process of traffic at signalized intersections is complex due to the conflict flows. Driver behavior at signalized intersections is directly relevant to traffic safety and performance. Thus, an insight into the driver behavior at intersections is significant both for practical application and for scientific study. Based on the category method proposed by Minderhoud (1999), driving task of a driver on an urban road can be mainly distinguished as:

- *The longitudinal subtasks* include all decisions related to longitudinal direction. For example: relative speed and distance from the preceding vehicle.
- *The lateral subtasks* include all decisions related to the lateral direction, such as lane changing decisions and overtaking behavior.

It is obvious that longitudinal and lateral tasks often occur together and are mutually influential to each other. Consequently, driver behavior can be simply classified into longitudinal driver behavior and lateral driver behavior. Traffic signals play an important role in urban traffic, therefore reaction to signals is separated from the behavior of longitudinal and lateral and introduced in an individual section. Several typical characteristics of driver behavior in urban areas will be addressed respectively in this appendix.

A.1 Longitudinal driving behavior

The longitudinal driver behavior mainly concerns the behavior in free flow and behavior under car-following conditions. When the distance to a preceding vehicle or to an intersection is sufficient large, drivers accelerate towards the free-flow speed or the allowed maximum speed. In relatively busy traffic flow or before an intersection, drivers have to adjust their speed and keep sufficient safe headways, i.e. driving under a car-following condition. The stimulus to the motion of a vehicle includes the movement change of the preceding vehicle, presence of conflicting vehicles, and signal control at a signalized intersection, etc. A driver reacts to these stimuli with a certain time delay which is denoted as 'reaction time'. In general terms, the main microscopic characteristics of longitudinal driving behavior include desired speed, desired headway, saturation headway, reaction time, desired acceleration/deceleration, and maximum acceleration/deceleration.

1. Desired speed

Without disturbance from other vehicles, drivers will drive at their desired speed with a small stochastic variation named as oscillation (PTV, 2013). In freeways, the desired speed is defined as the free speed which is the speed under free-flow conditions. In urban areas, the driving speed is often constrained by the speed limit, much lower than the free-flow speed on freeways. Therefore, the term desired speed is often used in research on urban traffic. In practical driving, if the current travel speed is lower than the desired or free-flow speed, the driver will estimate the necessity and opportunity of accelerating. Otherwise, the driver may change a lane or overtake to improve the present driving condition. In some simulation programs, like VISSIM, stochastic distributions of desired speeds are defined for each type of vehicles at different speeds, which models the variation of driver behavior (PTV, 2013).

In the literature, several researches focused on the estimation of the free-flow speed with real-life data. Hoogendoorn (2005) estimated the distribution of free speeds by Kaplan–Meier estimator (also known as the product limit estimator). The observations were censored with a composite time headway distribution model. This novel method was applied to establish free speed distributions with the data collected on two-lane rural roads in the Netherlands. Li *et al.* (2011a) reported that the desired speeds measured by GPS receivers in Changsha, a Chinese city, are much lower than the expected default values as given in the simulation program VISSIM.

Desired speeds (or free-flow speeds) can be influenced by a variety of factors. (Dixon *et al.* (1999) and Deardoff *et al.* (2011) studied the relation between the posted speed limit and observed free-flow speed on different type of roads: highways, urban streets and freeways in USA. The research results revealed that the average free-flow speed is strongly associated with the posted speed limit. Wang *et al.* (2006) used a laser speed gun to observe speed at intersections in China. This study revealed that the major contributing factors for approaching speed were site, rush-hour-status, traffic light condition, vehicle type, and driver gender. In particular, light status was the biggest contributor to speed. Kyte *et al.* (2001) found that free-flow speed is affected by pavement conditions, visibility, and wind speeds in USA. Camacho *et al.* (2010) collected free-speed data from fifteen freeway locations in Spain for almost three years. Results showed that bad weather conditions especially snow can reduce free-flow speed dramatically.

2. Desired/saturation headway

The term headway can be expressed either in time or in distance. Space headway (headway in distance) is an instantaneous variable and not easy to estimate by visual observations. One measuring method is to calculate the distance between two adjacent trajectories at the same time point in the time-space trajectories figure. The time headway indicates the time interval between two consecutive vehicles at a given location, e.g. stop line, and is much easier to measure. The 'desired headway' is defined as the headway the following driver wishes to keep with the preceding vehicle; while the ‘safe headway’ is used to denote the minimum safe headway the follower can keep under a certain driving condition. Desired headway and safe headway are often described in a function of the relative speed with the preceding vehicle. Gipps’ model was developed in terms of the concept of ‘safe distance’(Gipps, 1981), and is implemented in some commercial simulation programs, e.g. Aimsun (Barceló, 2011).

When the maximum capacity is reached at a signalized intersection, the flow is called the saturation flow. In saturation flow, drivers/vehicles are keeping short time headways, which are defined as *saturation time-headways*. The average saturation time headway can be approximately considered as the inverse of a saturation flow rate, which is especially relevant to the intersection capacity. The shorter the time headways are, the higher the lane capacity is. Even in a saturation flow, time headways still vary due to the diversity of driver behavior. Constant saturation time-headways can lead to a homogeneous and efficient traffic flow; whereas, variable saturation time-headways result in a heterogeneous and less efficient traffic flow. More details are analyzed in Chapter 4 and Appendix B.

3. Reaction time

Reaction time is a key factor in both longitudinal and lateral driving subtasks. It represents the driver’s ability to react timely to stimuli and make the corresponding decisions. Drivers adjust their speed by accelerating or decelerating after a certain response time. The response time depends on the characteristics of the driver and the performance of the vehicle. A driver need time to percieve the changing in driving environment, to process the information, and to implement his/her decision, which are associated with the driver’s experience and ability. The performance of the vehicle is mainly related to the vehicle category.

To avoid rear-end collisions, drivers have to detect the change in motion of the preceding vehicle. Leutzbach (1988) revealed that the follower cannot respond to the preceding vehicle if the distance between the two vehicles is large or the relative motion is too small. Hoffmann and Mortimer (1996) found that drivers’ reaction time is mainly determined by two factors: the distances between the vehicles and human properties. When the vehicles are close to each other, the sensitivity for the response is high, and vice versa. On the other hand, the response time depends on drivers’ perceptive ability, skills and experience. Some changes of the proceeding vehicle are very difficult to detect for the follower, e.g. small angular speed of the preceding vehicle (lower than 0.003 rad/s). In the literature, human characteristics of the response to the preceding vehicles inspired different longitudinal driving behavior models, for example psycho-spacing models / action point models, as illustrated in Figure A.1.

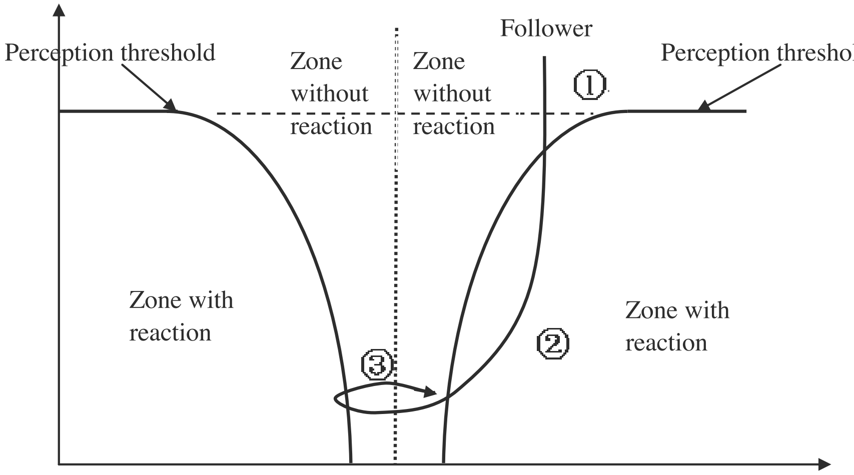


Figure A.1 Sketch of psycho-spacing models

In Figure A.1, the X-axis represents the speed relative to the preceding vehicle; and the Y-axis means the space headway. The preceding vehicle is assumed to drive at a constant speed. In state (1), the following driver catches up with the preceding vehicle with a constant relative speed. When the distance to the leader is lower than the perceptual threshold, the follower enters the "zone with reaction" and starts to decelerate, i.e. state (2). When the space headway decreases to the minimum safe distance, the driver adjusts his speed, slightly accelerating or decelerating. The relative speed is oscillating around zero, as state (3). In this situation, the space headway varies around a constant value. Based on the stimulus response theory, several well-known models (Leutzbach, 1988; Wiedemann, 1974) have been developed, and have been incorporated into some commercial simulation programs, such as VISSIM (PTV, 2013).

4. Desired/ maximum acceleration

The term maximum acceleration is defined as the maximum technically feasible acceleration. Drivers may apply the full acceleration power of the engine when trying to overtake or starting up from stand still. If drivers prefer driving in a more relaxed mode, they will apply a smaller acceleration, called the desired acceleration. In some simulation models, like VISSIM, desired acceleration and maximum acceleration are defined as functions of speeds with a certain statistical distribution to represent the variation of driver properties (PTV, 2013). However, the default profiles of desired acceleration and maximum acceleration are the same in VISSIM. Combustion engines reach their maximum acceleration at low speeds; afterwards desired acceleration and maximum acceleration both decrease with the increase of the speed. The desired acceleration is a crucial parameter in microscopic simulation models and should be calibrated with the locally collected data (Li *et al*., 2013).

5. Desired / maximum deceleration

Maximum deceleration is usually defined as the maximum technically feasible deceleration.

Drivers may apply the maximum deceleration in the case of emergency, such as an abrupt brake made by the preceding vehicle or a sudden lane change from an adjacent lane. A gentle deceleration may be applied when approaching a known or visible obstacle, such as a traffic light or a slowly moving vehicle in front. The desired deceleration is generally lower than the maximum deceleration.

A.2 Lateral driver behavior

The lateral driving maneuvers are conducted for: maintaining an appropriate lateral position in the lane, lane changing, overtaking, and curving. Since lane changing and overtaking incorporate longitudinal movement and lateral movement, these two maneuvers are more complex compared with the position maintaining maneuver and attract more attention from researchers. The behavior of curving is not strongly related to the subject of this dissertation and is not discussed in this appendix.

1. Lane changing behavior

A lane changing process often includes two steps: the selection of a lane and the execution of lane changing. According to the reason of lane changing, two kinds of lane changing is classified: mandatory (MLC) and discretionary (DLC) (Sun and Elefteriadou, 2011). MLC is executed when the driver must leave the current lane. DLC is performed to improve the present driving conditions. The feasibility of lane changing is similar to a probability of gap acceptance, because drivers need to evaluate the gaps between two consecutive vehicles on the target lane. Gap-acceptance models were initially developed to explain the crossing behavior at intersections. The required minimum gap is also crucial to a lane change.

In the literature, limited research has been conducted to address the probability of changing lanes based on driver behavior with field data. Sun and Elefteriadou (2010) studied the correlation between the probability of lane changing and driver behavior. The data were collected from: a focus group survey and an in-vehicle driving test. Gurupackiam and Jones (2011) investigated the variations in accepted gap and lane changing durations under different traffic conditions in urban areas. The results revealed that the mean value of accepted gaps was statistically different between free flow and congested flow. Drivers were inclined to accepted smaller gaps under congested traffic conditions than in free flow. However, the duration of a lane change did not vary substantially between different traffic conditions.

2. Overtaking behavior

If drivers are following a slow-moving vehicle, another way to improve the present driving conditions is to overtake. In urban areas, overtaking on a road with separated driving lanes without opposing traffic can be considered as executing lane changing twice in a given time. Gap acceptance models are often used to describe the overtaking process. Generally, drivers who want to execute overtaking also need to estimate the required ‘gap’, and then compare it with the available ‘gap’. If the available gap is larger than the required one, overtaking is executed; whereas, it has to be postponed. The term ‘gap’ is quantified in ‘time’ more often than in ‘distance’.

The available gap is dependent on the present traffic situation. The minimum accepted gap, often named as ‘critical gap’, is relevant to the characteristics of the driver, the vehicle performance and the road conditions. Therefore, different drivers are characterized with different critical gaps which have a specific distribution in a given situation.

Gap acceptance is important to operation of driving, driving safety and simulation models. Many different methods have been developed to estimate the distribution of critical gaps. After comparing some critical gap estimation methods, Brilon *et al*. (1999) recommended the maximum likelihood procedure (Troutbeck, 1992) and the method developed by Hewitt (1983) for practical application. It is difficult to collect data for gap acceptance study in real traffic. Vehicle simulators in laboratories are becoming an alternative to field study. However, the validity of driving simulators are often doubted because the test drivers maybe behave differently from what they do in reality (Kaptein *et al*., 1996). The ‘gap-creation’ concept is introduced into some elaborate models, like DRACULA (Liu, 2007). In reality, some drivers in the priority flow may deliberately slow down to create a gap for the waiting vehicle. A parameter in DRACULA is used to represent the percentage of drivers who are willing to create a courtesy gap (Bonsall et al., 2005).

A.3 Reaction to signals

In this dissertation, the term “signalized intersection” indicates both fixed and variable signal controlled intersections. The reaction to traffic signals can be simply described by start lag and end lag.

1. Start lag

At the start of a green phase, drivers need some time to react to the signal and to accelerate their vehicles. The time headway of discharging vehicles decreases from the first vehicle up to the third or until the eighth, because the first few vehicles are still accelerating while passing the stop line (Branston and van Zuylen, 1978). After a few vehicles the time headway becomes constant. The start lag or the start-up lost time is the sum of the first several vehicles’ headways minus the average constant headway (HCM, 2000).

The start lag is partly due to the reaction time of the first few drivers, but it is mainly ascribed to the fact that vehicles have to accelerate. Therefore, the speed of the first few vehicles is lower than that of other vehicles in the middle of the green phase. In short, the start lag represents the reaction time and the acceleration characteristics of the first several vehicles in the queue. Owing to the variation in driver behavior, start lags can vary significantly in different countries. For example, the start lag in the through going lanes in the Netherlands is about 2 seconds, while this value is about 4 seconds, or even 8 seconds at the investigated Chinese intersections (Li *et al*., 2012).

2. End lag

After the green phase, a part of the yellow phase can be still used by vehicles to enter the intersection. This part of the yellow phase is named *end lag* which can be seen as a kind of extension of the effective green time. When calculating the intersection capacity and cycle time with some formulae, like Webster formula (Webster, 1958), *end lag* is a kind of input parameter and the value should be determined by the local driver behavior. The default value of *end lag* in some programs, e.g. VRIGen, is 1 second or 2 seconds which represents drivers' reaction to the yellow light (VRIGen, 2007). The comparison of end lags in different countries has not been addressed in the literature. The possible reason is that end lags can only be observed in fully saturated green phases. Accordingly, the data regarding end lags are not easy to collect if the traffic is not over saturated.

Based on the above analysis, start lag and end lag can be considered as quantified characteristics of driver behavior and vehicle properties at signalized intersections. Start lag and end lag can be measured through several methods: regression method, average headway method, etc. More details are explained in Chapter 4 and Appendix B.

A.4 Conclusions

In this appendix, several typical characteristics of driver behavior in urban areas are introduced and summarized. Longitudinal driver behavior mainly includes desired speed, desired headway, saturation headway, reaction time, desired and maximum acceleration/deceleration, which come into being the core of microscopic models. The diversity of driver behavior also can be explained by different subjective preferences (such as desired speed, desired minimum gap distance, desired acceleration), which can directly impact traffic performance and traffic safety. Lateral driver behavior is mainly related to lateral position maintaining, lane changing, and overtaking. Reaction to signal is the typical driver behavior at signalized intersections with the characteristics: start lag and end lag.

Appendix B

Saturation Flow Rate Estimation Methodology[6]

This appendix mainly focuses on the discussion of the saturation flow rate estimation methodology. Some research results which have been introduced in Chapter 4 will not presented again in this appendix.

In Chapter 4, significant differences have been found in the saturation flow characteristics between China and the Netherlands. In the investigated intersections, saturation flow rates in Chinese cities were 20~30% lower than the ones in Dutch cities. In order to confirm these conclusions, the methods for the estimation of saturation flow rates at signalized intersections are compared in this appendix. The regression method gives the most informative results. The inverse headway method is simple, but the estimation of saturation flow rate is biased. The product limit method, utilizing the information of both unsaturated flow and saturated flow, can directly estimate the distribution of saturation flow rate.

B.1 Regression method

There are several ways to determine the saturation flow rate, the start lag end lag and the pcu values. Before 1978 the most frequently used method was to count the passing vehicles in every period of 5 seconds and take the average, ignoring the first time period in the green phase and all under saturated time periods (TRRL, 1963). Nowadays, the method described in the Highway Capacity Manual (HCM, 2000) is commonly used. In practice, engineers often use the approximate models to calculate the saturation flow rate based on lane width, gradient, presence of bus stops etc., instead of verification with real traffic flows. Branston and van Zuylen (1978) developed a sophisticated, but still simple method to estimate saturation flow rate, pcu values, start and end lags simultaneously.

As discussed in Chapter 4, the number of vehicles that crosses the stop line during a time period T is:

[6] This appendix is based on the paper: Measuring the Saturation Flow, Lost Time, and Passenger Equivalent Values of Signalized Intersection (2010), by van Zuylen H., and J. Li, Proceedings of *7th International Conference on Traffic and Transportation Studies (ICTTS 2010)*, 383: 312-329, Kunming, China.

$$n = s\,T - p_1\,n_1 - p_2\,n_2 - p_3\,n_3 - b\,s\,\lambda_1 + e\,s\,\lambda_2 + \varepsilon_i \quad \text{(B.1)}$$

where

s : the saturation flow rate,

n : the number of passenger cars,

n_1: the number of busses,

n_2: the number of lorries,

n_3: the number of articulated lorries,

p_1: the pcu value of buses,

p_2: the pcu value of lorries,

p_3: the pcu value of articulated lorries,

λ_1: the start lag, $b = 1$ for time intervals starting at the beginning of a green phase, otherwise $b = 0$,

λ_2: the end lag, $e = 1$ for a time interval ending at the beginning of a yellow phase, otherwise $e = 0$.

ε_i : the error due to/caused by non systematic deviations of the traffic process from the supposed model.

If the parameters in function (B.1) are normally and independently distributed, these parameters can be estimated by multiple linear regressions. By minimizing the difference between the observed and the modeled flow profiles, Radhakrishnan and Mathew (2011) proposed a similar method for the estimation of saturation flow rate and pcu values.

There is some approximation involved in function (B.1). About the length of the start lag, HCM 2000 assumes that after the fourth vehicle the traffic flow is stable, while Bonneson (1992) found that the start lag can be influenced by the intersection type. According to the observations presented in Chapter 4, the number of the vehicles that experience the start-up delay is different between the Chinese intersections and the Dutch ones. In the Netherlands only the first two or three drivers were affected by the start-up delay, while at the Chinese intersections first four to six drivers moved relatively slowly at the beginning of green phases. In Chapter 4, the main causes for the long start lag and low saturation flow rate at Chinese intersections are identified as: traffic rules offences and the presence of conflicting vehicles. The influence of these two factors on saturation flow rates has been modeled by adding two variables q_1 and q_2 to the regression saturation flow function (B.1).

$$n = s\,T - p_1\,n_1 - p_2\,n_2 - p_3\,n_3 - q_1 m_1 - b\,(q_2\,m_2 + s\,\lambda_1) + e\,s\,\lambda_2 + \varepsilon_i \quad \text{(B.2)}$$

where

m_1: the number of traffic rule offence which influence the normal traffic flow

q_1 : the influence factor of traffic rule offence

m_2: the number of conflicting vehicles which still stay at the intersection at the start of green phase

q_2: the influence factor of non-cleared vehicles

The parameters in Function (B.2) can be estimated by linear regression. The values of q_1 and q_2 are determined as 0.33 and 1.41 respectively for one intersection in Chengdu, China. That indicates that every conflicting vehicle at the start of the green phase can reduce 0.33 vehicles passing the stop line and every offence can block 1.41 vehicles. According to the modified regression method (B.2), the saturation flow rate, start lag, end lag, pcu values, and the influence of other factors on saturation flow rates can all be estimated.

B.2 Inverse time headway method

The saturation flow rate can also be seen as the inverse of the saturation time headway between consecutive vehicles. That is the way introduced by HCM 2000 to investigate saturation flow rate: the inverse of the average headways between vehicles after the fourth in the queue. It is clear that different classes of vehicles have different (average) headways. A bus or (articulated) lorry will need more time to pass an intersection than an ordinary passenger car. To deal with this difference, the concept of *passenger car unit* (pcu) is introduced, the ratio of the average time needed by a vehicle of a specific class and the average time needed by a passenger car (Kimber, 1985). In HCM, pcu is defined as passenger-car equivalents (PCE).

The analysis of headways is an effective method to reveal the differences in driver behavior. In Chapter 4, the headway distributions have been measured and analyzed for 4 Chinese and 4 Dutch intersections, and significant differences between the two countries have been found. However, saturation flow rates derived from headways are different from the ones derived directly from regression, as discussed by Kimber (1985). This conclusion also applies to the estimation of pcu values. The assumption that the saturation flow rate is just the inverse of the headway is too simplistic. In the following, it will be shown that the inverse of the headway underestimates the saturation flow rate because of the statistical variation of headways.

The number of cars that can pass in a certain time t is $\sum_{i=1}^{n} h_i$. The quantity h is stochastic because the time headways are variable. The probability $P_n(T)$ that n vehicles have past the stop line in a certain time T can be calculated as:

$$P_n(T) = p(\sum_{i=1}^{n} h_i \leq T).p(\sum_{i=1}^{n+1} h_i > T) \qquad \text{(B.3)}$$

i.e. the probability $p(\sum_{i=1}^{n} h_i \leq T)$ means that the summation of n headways is less than T. If the headways are mutually independent, the variance of the sum of headways is proportional to the number of headways in the sum. So the variance of n headways is $n*\sigma$, where σ is the variance of a single headway. To simplify the computation, the probability distribution of the sum of n headways is assumed to be a uniform distribution between $n.\bar{h} - \sigma\sqrt{3n}$ and $n.\bar{h} + \sigma\sqrt{3n}$. The probability $p(\sum_{i=1}^{n} h_i \leq T)$ is the cumulative distribution as shown in Figure B.1.

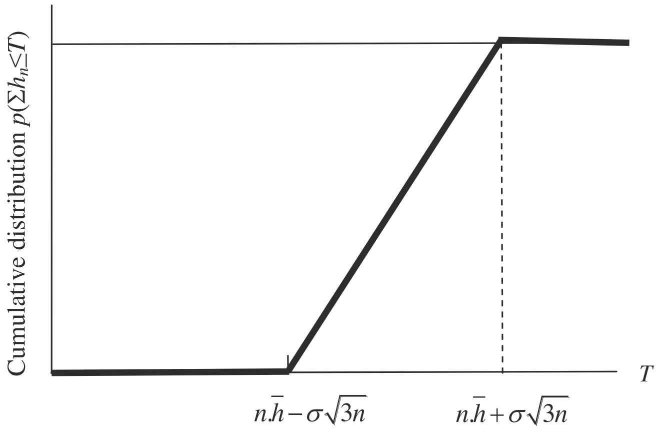


Figure B.1 Cumulative probability distribution of headways, assuming a uniform probability distribution with a standard deviation σ

The probability of $p(\sum_{i=1}^{n} h_i \leq T)$ is 1 - $p(\sum_{i=1}^{n} h_i > T)$, i.e.

$$
\begin{aligned}
p(\sum_{i=1}^{n} h_i \leq T) &= 0 && \text{if } T < n\bar{h} - \sigma\sqrt{3n} \\
&= 1 && \text{if } T > n\bar{h} + \sigma\sqrt{3n} \\
&= (T - n\bar{h} + \sigma\sqrt{3n}) / 2\sigma\sqrt{3n} && \text{if } n\bar{h} - \sigma\sqrt{3n} \leq T \leq n\bar{h} + \sigma\sqrt{3n}
\end{aligned}
\tag{B.4}
$$

Similarly the probability $p(\sum_{i=1}^{n+1} h_i > T)$ is

$$
\begin{aligned}
p(\sum_{i=1}^{n+1} h_i > T) &= 1 && \text{if } T < (n+1)\bar{h} - \sigma\sqrt{3(n+1)} \\
&= 0 && \text{if } T > (n+1)\bar{h} + \sigma\sqrt{3(n+1)} \\
&= 1 - (T - (n+1)\bar{h} + \sigma\sqrt{3(n+1)}) / 2\sigma\sqrt{3(n+1)} \\
& && \text{if } (n+1)\bar{h} - \sigma\sqrt{3(n+1)} \leq T \leq (n+1)\bar{h} + \sigma\sqrt{3(n+1)}
\end{aligned}
\tag{B.5}
$$

Using these formulas, the average number of vehicles $\bar{n}$ that can pass the stop line in a time period T can be determined under the assumption that the period starts just after the passing of a vehicle (so that the next vehicle needs a full headway).

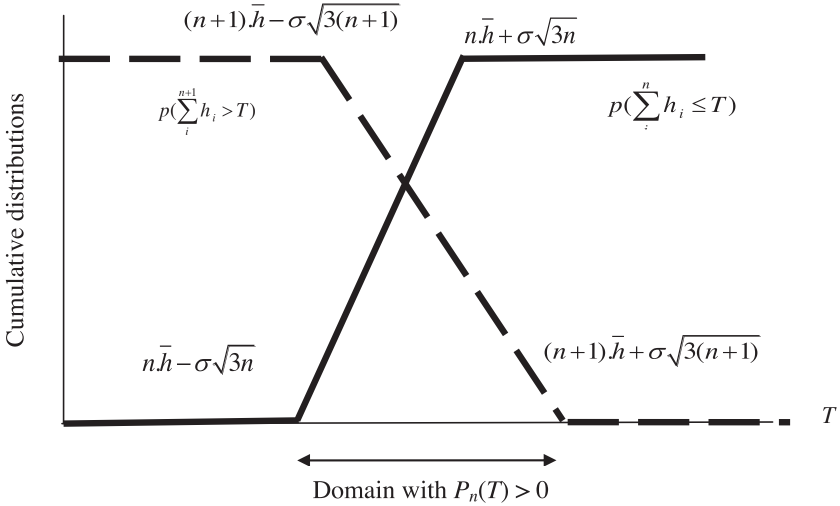


Figure B.2 Probability of *n* headways fitting in a time interval *T*

The relative position of the two probability curves with respect to each other depends on the value of n and σ, as shown in Figure B.2.

$$n\bar{h}-\sigma\sqrt{3n} < (n+1)\bar{h}-\sigma\sqrt{3(n+1)} \quad \text{i.e.} \quad \bar{h} > \sigma(\sqrt{3(n+1)}-\sqrt{3n}), \text{ or}$$
$$n\bar{h}-\sigma\sqrt{3n} > (n+1)\bar{h}-\sigma\sqrt{3(n+1)} \quad \text{i.e.} \quad \bar{h} < \sigma(\sqrt{3(n+1)}-\sqrt{3n})$$

It is easy to see that the average number $\bar{n}$ of vehicles that pass during the time T is larger than $T/\bar{h}$, or

$$\bar{h} > T/\bar{n} \quad \text{and} \quad \bar{s} > 1/\bar{h}$$

The expected throughput of the stop line is at least 0.5 vehicle larger than $T/\bar{h}$ if the standard deviation of the headways is zero or very low. This is consistent with the observation made by Branston and van Zuylen (1978). They found that the regression of the number of discharged vehicles as a function of the time differs from the regression of the time as a function of the number of discharged vehicles. For a long time period, this 0.5 vehicle is only a small fraction of the total outflow. With the increase of standard deviation, this difference becomes large. As an example, the saturation flow rates estimated from $3600/\bar{h}$ are compared with the values estimated with the regression method for three intersections in Chinese cities, as shown in Table B.1. Apart from two cases, the saturation flow rates that are directly estimated with the regression method are larger than the ones calculated by inverse time headway.

Table B.1 Comparison of saturation flow rates estimated by regression and inverse headway

City	Intersection	Lane	Regression method		Inverse headway method		
			s (pcu/h/ln)	SD	$\bar{h}$	SD	$3600/\bar{h}$
Beijing	Dong Z.M.	TH_L	1415	187	2.5782	0.7564	1396
		TH_R	1736	229	2.3665	0.4464	1521
Chengdu	Ba B.J._South	TH_L	1457	94	2.5008	0.7592	1439
		TH_R	1557	135	2.4694	0.7902	1458
	Dong C.G	TH_L	1573	74	2.4177	0.8556	1489
		TH_R	1436	92	2.4729	0.9472	1456
Changsha	FuR.L_N.2008	TH_L	1335	59	2.6904	0.9792	1338
		TH_M	1526	42	2.4118	0.7604	1493
	FuR.L_N.2009	TH_L	1436	37	2.6175	0.8873	1375
		TH_M	1487	41	2.4121	0.9188	1492
	FuR.L _S.2009	TH_L	1552	65	2.5371	1.1861	1419
		TH_M_L	1556	76	2.5060	1.0655	1437
		TH_M_R	1615	80	2.4328	1.1622	1480
		TH_R	1831	159	2.2947	1.1148	1569

Note: TH_L indicates the left-most through going lane;
TH_R indicates the right-most through going lane;
TH_M indicates the median through going lane;
TH_M_R indicates the right one of the two median through going lanes;

The conclusion is that measuring headways is not the best way to determine saturation flow rates if one assumes that: $\bar{s}=1/\bar{h}$. The measurement of headways is important and relevant for the quantification of the driver behavior, but the link between the headway and the saturation flow rate deserves special attention. The next section discusses how to estimate the distribution of saturation flow rates with the information collected from both under saturated and fully saturated flows.

B.3 Product limit method

The product limit method (PLM) developed by Kaplan and Meier (1958) is often used to estimate the survival function from lifetime data. In medical research, it can be measured by PLM that the probability of patients living for a certain amount of time after a certain treatment. An important advantage of the PLM is to extract information from censored data, which occurs if a sample withdraws from a study. If no censoring occurs, PLM just outputs an empirical distribution function. Hyde and Wright (1986) independently developed a method to determine saturation flow rates from asymptotic values of observed saturation flow rates during a green phase. They were not able to determine whether the observed flow was saturated or not because there was an upstream bottleneck. The method developed for this situation can be seen as a simplified version of the product limit method. Chen *et al*. (2009) used the product limit method to study the reliability of capacity at signalized intersections. In their study, the data were from simulation program VISSIM, not collected in reality.

When the PLM is introduced to estimate the probability distribution function $f(s)$ of the saturation flow rate, the observations can include under saturated flows together with saturated flows. The right censored observations are that the flow rates are lower than the saturation flow rate (e.g., the queue is no longer present upstream of the intersection). The observations of right censored flows indicate that: the saturation flow rate is larger than the observed flow rate in an under-saturated situation. In a fully saturated time period, the probability distribution function of saturation flow rate s_i is $f(s_i)$. In an under saturated flow period, the flow rate v_i is lower than the saturation flow rate.

In the PLM an indicator δ is introduced. The value of $\delta = 1$ if the observed flow is under saturated; otherwise $\delta = 0$.

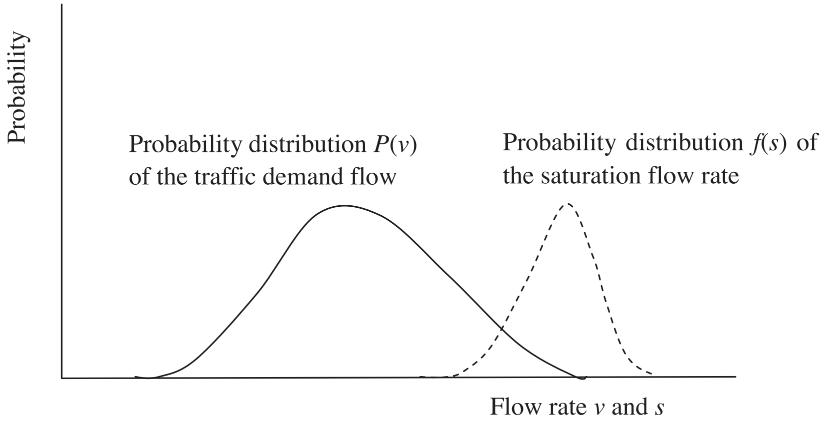


Figure B.3 The probability distribution of the demand flow rate and the saturation flow rate (Hoogendoorn, 2007).

The probability distribution of the traffic demand rate $P(v)$ can be determined from observations upstream of the intersection or it can be assumed to be a Poisson distribution determined by the average flow. The probability that a certain observed flow rate v is lower than the saturation flow rate s is given by:

$$P(\delta = 1 | v) = \int_v^\infty f(x)dx \tag{B.6}$$

For a series of observations of traffic flow rate v_i, the likelihood is given by:

$$L\{v_i\} = \prod_{i=1}^{n} \left[\int_{v_i}^{\infty} f(x)dx \right]^{\delta_i} f(v_i)^{1-\delta_i} \tag{B.7}$$

If the probability distribution function $f(s)$ is known or pre-determined, e.g. a normal distribution, the parameters of this distribution function can be estimated by maximizing the likelihood function (B.7). In this case, PLM is categorized as 'Parametric Product Limit Method'.

If there is no real evidence for the choice of a particular function for the probability distribution, 'Non-parametric Product Limit Method' is applied. The probability $P(\delta = 1 | v)$ is that in an observation period the queue has disappeared. It depends on the cycle time, green time and load ratio of the stop line and can be determined from empirical function:

$$P(\delta = 1 | v) = \frac{1}{n}\sum_{i=1}^{n}\delta_i \tag{B.8}$$

The limitation of the product limit method is difficult to explain the variation in saturation flow from cycle to cycle. The regression method has this possibility, but cannot give a distribution of the saturation flow rate. The main limitation of the regression method is the restriction on saturation flow. It is possible to the regression method to estimate the end lag of green phase. But it is difficult to observe when the intersections are well controlled, i.e. without overflow queues at the end of the green phase.

B.4 Case study

Both regression method and HCM method are used to estimate saturation flow rates for a signalized approach of a bridge in Changsha, China. Green phases are distributed to the vehicles from ramps and Wuyi Road respectively. The observation time is from 11:45am to 13:15pm on 29, Dec. 2009. The calculation results are shown in Table B.2. Both on the onramp and the Wuyi Road, the saturation flow rates estimated by regression method are larger than those calculated by HCM method.

Table B.2 Comparison of saturation flow rates calculated by two methods

Method		*s*(veh/ln/h)	R^2	*F*	*p*-value	error variance	Standard deviation
Ramp	Regression	1630	0.95	513.0	0	0.473	
	HCM method	1536					189
Wuyi Rd	Regression	1732	0.98	1908.6	0	1.417	
(Arterial)	HCM method	1676					147

The saturation flow rate distribution of Wuyi Road was estimated by PLM based on two methods: parametric method and non-parametric method. The applied mean saturated flow rate was set at 1800 pcu/h, which is a representative saturation flow rate of one lane on urban roads in China. A normal distribution with a standard deviation of 10% was chosen to generate stochastic saturated flow rate. In this example, about 25% of the observed flow rates were saturated flows. Three saturation flow rate distributions were calculated by:

- Empirical Distribution, which is the normal distribution with a standard deviation of 10%;
- Parametric (normal distribution) PLM method;
- Non-parametric PLM method.

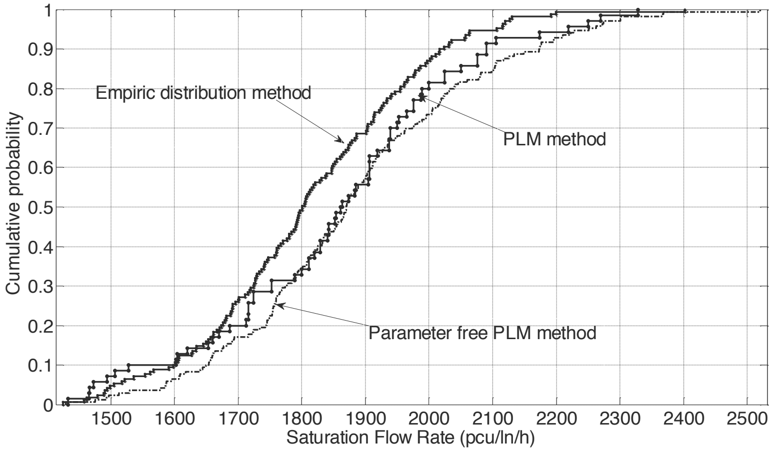


Figure B.4 Estimating the saturation flow rate distribution based on different estimation methods

The fact that the PLM method gives a 3 to 4% higher value for the saturation flow rate might be explained by the fact that the lane capacity is lower for cars driving under congested conditions than that in free flow. PLM also takes the free-flow conditions into account.

B.5 Conclusions

This appendix presents three methods for estimating saturation flow rates at signalized intersections and ramps. The three methods are:

- the regression method,
- the inverse time headway method, and
- the product limit method.

The first method is only applicable for observation periods that are fully saturated. It has the advantage that several explanatory factors can be included, such as traffic offences and quality of the traffic control. It also offers the possibility to analyze start-up delays and the utilization of the first seconds of the yellow phase. The regression method shows which factors, with corresponding measures, can be expected to improve the saturation flow rates. The inverse time headway method gives a general underestimation of the saturation flow rate. However, it offers a convenient way to analyze the differences between different vehicle categories. The product limit method is not limited to the observations of fully saturated flows and can estimate a probability distribution of the saturation flow rate. Both the observation of saturated flow and unsaturated flow can be used to determine the saturation flow rate distribution. Disturbances of external factors to the traffic flow are included, but cannot be directly separated.

Appendix C

Driver Behavior Questionnaire

Note: This Driver Behavior Questionnaire (BDQ) was published online in two languages: http://www.sojump.com/jq/2146887.aspx (Chinese), and
http://www.thesistools.com/web/?id=330853 (Dutch).
The DBQ survey results are presented in Chapter 5. The following questions are the English translation of the Dutch and Chinese questionnaires.

1. **Gender:______**
2. **Age: ______**
3. **Education:**
   - Master or higher than Master
   - University
   - Professional education
   - Others
4. **Your present occupation:**
   - Full- time student
   - Teacher/ Researcher
   - Technician/Professional person (Lawyer, Doctor, Consultant, Accountant, Architect, Journalist, etc.)
   - Professional driver
   - Administrative staff
   - Business person
   - Nurse
   - Manual Worker
   - Police / Army
   - Farmer
   - House woman/man
   - Retired person
   - Unemployed
   - Others

5. **Driving experience (Years):** ______

6. **Distance traveled per year:**
   - <5,000 km
   - 5,000~10,000 km
   - 10,000~30,000 km
   - 30,000~50,000 km
   - >50,000 km

7. **Driving frequency (To work and from work are 2 trips, and a single roundtrip is one trip):**
   - <1/week
   - 1 ~ 3/ week
   - 4 ~ 7/week
   - >3/day

8. **The ownership of the vehicle often driven by you (more than one answer is allowed)**
   - Your sedan
   - Other's sedan
   - Company/ Institute
   - Lease vehicle
   - Others

9. **Number of motor vehicles in your family:**_______

10. **Do you enjoy driving?** (1 indicates dislike, and 10 is for enjoying very much)

11. **Please move the slide block to select which type of driver you are.** (1 indicates the most conservative drivers, and 10 is for the most aggressive drivers)

12. **What kind of driver you are in your family and friends' impression?** (1 indicates the most conservative drivers, and 10 is for the most aggressive drivers)

13. **Do you have good driver skills?** (1 indicates very poor, and 10 means excellent)

14. **How many times have you been recorded by the traffic police for traffic rule offences last year?** ______

15. **How many traffic accidents have you been involved during the past 5 years?** If you have been involved, please write down what kind of accidents they are. _________
    (Note: exclude the minor accidents in which only one side is involved, like bumping a wall while reversing)

16. **Do you use mobile phone by holding it in your hand during driving?**
    - Never
    - Nearly never
    - Seldom
    - Sometimes
    - Often

17. **Do you cross a solid line to make a lane change?**
    - Never
    - Nearly never

- Seldom
- Sometimes
- Often

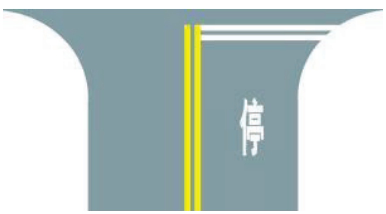
18. **When another driver's irregular driving behavior causes danger to you. Do you start to chase him and try to warn him with words or gestures?**
- Never
- Nearly never
- Seldom
- Sometimes
- Often

19. **Please indicate the meaning of the road side traffic signs:**

Left: Never seen
Left: Don't know
Left: I know: ________

Right: Never seen
Right: Don't know
Right: I know: ________

20. **Please indicate the meaning of the traffic signs on the pavement:**



Left: Never seen
Left: Don't know
Left: I know: ________

Right: Never seen
Right: Don't know
Right: I know: ________

21. **Do you have the habit to search a priority sign when you are approaching an intersection?**
- DD Generally would not (<10%)
- More likely would not (10% to 40%)
- Sometimes would, sometimes would not (40% to 60%)
- More likely would (60% to 90%)
- Generally would (>90%)

22. **At an un-signalized intersection, you are driving straight on from a minor street. Do you give priority to the vehicles from the arterial street? (The arterial street has priority shown by road marking and / or a road side sign.)**

- Generally would not (<10%)
- More likely would not (10% to 40%)
- Sometimes would, sometimes would not (40% to 60%)
- More likely would (60% to 90%)
- Generally would (>90%)

23. **Do you give priority to the through going vehicles when you are turning left at an intersection?**
    - Generally would not (<10%)
    - More likely would not (10% to 40%)
    - Sometimes would, sometimes would not (40% to 60%)
    - More likely would (60% to 90%)
    - Generally would (>90%)
24. **Do you give priority to pedestrians on a pedestrian crossing when you are turning right at an un-signalized intersection?**
    - Generally would not (<10%)
    - More likely would not (10% to 40%)
    - Sometimes would, sometimes would not (40% to 60%)
    - More likely would (60% to 90%)
    - Generally would (>90%)
25. **In which case will you not give priority to pedestrians when you are turning right and sharing the green phase with the pedestrians?** (more than one answer are available)
    - Never happens because I always give priority to pedestrians
    - Pedestrians never have priority
    - Congested traffic situation
    - When I am in a hurry
    - Too many pedestrians, and too long time waiting make me lose patience
    - Others, for example ________
26. **Do you cross the stop line during a red phase when you know there is not a red-light registration camera?**
    - Never
    - Nearly never
    - Seldom
    - Sometimes
    - Often
27. **Do you cross the stop line during a yellow phase, when you know you can cross the stop line before the red light?**
    - Generally would not (<10%)
    - More likely would not (10% to 40%)
    - Sometimes would, sometimes would not (40% to 60%)
    - More likely would (60% to 90%)
    - Generally would (>90%)
28. **Have you almost been hit by a following car when you suddenly braked in a yellow**

phase?
- Never
- Nearly never
- Seldom
- Sometimes
- Often

29. **When waiting in a red phase, have you ever been distracted so that you didn't react to the green light in time until other people mentioned you?**
- Never
- Nearly never
- Seldom
- Sometimes
- Often

30. **In a yellow phase, did you ever almost collide with the preceding vehicle when the preceding car suddenly braked?**
- Never
- Nearly never
- Seldom
- Sometimes
- Often

31. **You drove into the wrong lane when approaching a signalized intersection.**
- Never
- Nearly never
- Seldom
- Sometimes
- Often

32. **Do you ignore the speed limit in urban areas when you are driving in a main road without much traffic?**
- Generally would not (<10%)
- More likely would not (10% to 40%)
- Sometimes would, sometimes would not (40% to 60%)
- More likely would (60% to 90%)
- Generally would (>90%)

33. **Under a normal traffic condition, you were so close to the preceding vehicle that you would have a collision when the front vehicle suddenly braked.**
- Never
- Nearly never
- Seldom
- Sometimes
- Often

34. **When you are following a slow-moving vehicle, you become impatient and try to change lanes as soon as possible.**
- Generally would not (<10%)

- More likely would not (10% to 40%)
- Sometimes would, sometimes would not (40% to 60%)
- More likely would (60% to 90%)
- Generally would (>90%)

35. **When you are followed by or are following a big truck, you feel unsafe and try to change lanes as soon as possible.**
    - Generally would not (<10%)
    - More likely would not (10% to 40%)
    - Sometimes would, sometimes would not (40% to 60%)
    - More likely would (60% to 90%)
    - Generally would (>90%)
36. **Do you turn on the indication light when you drive off or change lanes?**
    - Generally would not (<10%)
    - More likely would not (10% to 40%)
    - Sometimes would, sometimes would not (40% to 60%)
    - More likely would (60% to 90%)
    - Generally would (>90%)
37. **Do you often check the mirrors when you are going straight on?**
    - Never
    - Nearly never
    - Seldom
    - Sometimes
    - Often
38. **Do you check the side mirrors and also look over your shoulder when you try to drive off or to change lanes?**
    - Generally would not (<10%)
    - More likely would not (10% to 40%)
    - Sometimes would, sometimes would not (40% to 60%)
    - More likely would (60% to 90%)
    - Generally would (>90%)
39. **You suddenly crossed a solid line to make a lane change because the traffic was faster or the queue was shorter in the other lane.**
    - Never
    - Nearly never
    - Seldom
    - Sometimes
    - Often
40. **You still conduct overtaking even when you see the preceding vehicle already turns on the left turning indicator.**
    - Never
    - Nearly never
    - Seldom
    - Sometimes

- Often

41. **You overtake a slow-moving vehicle on the right side when there is no possibility on the left side.**
    - Never
    - Nearly never
    - Seldom
    - Sometimes
    - Often
42. **You underestimated the speed of the oncoming vehicle when overtaking on a two-lane road.**
    - Never
    - Nearly never
    - Seldom
    - Sometimes
    - Often
43. **Before executing overtaking, you check whether there is another car overtaking you.**
    - Generally would not (<10%)
    - More likely would not (10% to 40%)
    - Sometimes would, sometimes would not (40% to 60%)
    - More likely would (60% to 90%)
    - Generally would (>90%)
44. **You keep driving in the left-most lane even there is no traffic in the other lanes and you don't have to turn left.**
    - Never
    - Nearly never
    - Seldom
    - Sometimes
    - Often
45. **You remain on a lane at high speed even when you know this lane will end soon. At the last point, you make a forced lane change to the other lane.**
    - Never
    - Nearly never
    - Seldom
    - Sometimes
    - Often
46. **In congestion, you lose patience to wait for a sufficient gap and make a forced lane change to the target lane.**
    - Generally would not (<10%)
    - More likely would not (10% to 40%)
    - Sometimes would, sometimes would not (40% to 60%)
    - More likely would (60% to 90%)
    - Generally would (>90%)
47. **When you drive in the lane next to the one that will be end/closed, will you allow the**

drivers in that lane to move to your lane?
- Generally would not (<10%)
- More likely would not (10% to 40%)
- Sometimes would, sometimes would not (40% to 60%)
- More likely would (60% to 90%)
- Generally would (>90%)

48. **In congestion, another vehicle in the adjacent lane tries to have a forced lane changing in front of you. Will you decelerate and provide the vehicle a gap to merge?**
- Generally would not (<10%)
- More likely would not (10% to 40%)
- Sometimes would, sometimes would not (40% to 60%)
- More likely would (60% to 90%)
- Generally would (>90%)

49. **If you see conflicting vehicles still staying at the signalized intersection while your signal is turning to green, what are your usual reactions?** (more than one answer are available)
- Still driving, because it is my green time
- Giving priority to the conflicting vehicles because they are from the previous phase
- Depend on the traffic situation: in congestion, if other people squeeze me, I will also squeeze the conflicting vehicles
- Depend on my situation: hurry then squeeze the conflicting vehicles
- Others

50. **Your E-mail:__________________ (If you want to get the survey results)**

Appendix D

Focus Group Discussion Question List

Note: The questions listed in this appendix have been discussed in six driver behavior focus group sessions organized in June 2013 in Changsha, China. More details about the discussion are introduced and concluded in Chapter 7. The questions are English translations from the original Chinese version.

1. **Opening questions**
   - What do you think about Chinese people's driving behavior? Why?
   - Is your driving style conservative or aggressive?
   - What factors can significantly influence your driving style? What driving characteristics can be influenced?
   - Do you enjoy driving? Why?

2. **Application 1: Car following behavior**
   - What issues are important to 'car following'?
   - In what cases can you keep patient with car following? In what situations will you easily you lose patience?
   - Do you always guard against a sudden brake of the preceding driver by keeping a little larger headway than the normal one?
   - Do you always think that other people will make a forced or a sudden lane change, and do you often keep a little larger headway than the normal one?
   - What factors can influence the distance which you will keep from the preceding vehicle? Please fill in the following table.

Factors affecting car following distance (1 = least important, 5 = most important)

Possible Factors	1	2	3	4	5
Your Speed					
Speed of the preceding vehicle					
Driving task and personal mood					
Road configuration: slope, lane width, curve					
Category of the preceding vehicle (bus, truck)					
Pavement conditions					
Weather					
Signaling conditions (evening/daytime)					

3. Application 2: Lane changing behavior

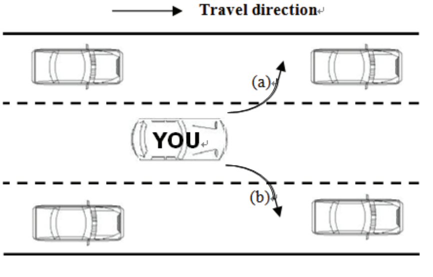
- What issues are most important to "lane changing"?
- What kind of lane changing behavior do you dislike?
- Do you accelerate or decelerate while changing lanes?
- Discussion of the likelihood of a lane-change

  Suppose you are driving in an urban street with three lanes. Please evaluate the level of likelihood (from 1 to 5) of lane changing for each listed reason according to your driving experience. You have two different driving tasks: for commuting, and for leisure at weekends.

Likelihood of making a lane change (1 = generally would not, 5 = generally would)

Scenario	Commuting					Leisure				
	1	2	3	4	5	1	2	3	4	5
Stopped bus at a bus stop										
Another vehicle merging into your lane										
Slow-moving vehicle ahead										
Shorter line of queuing vehicles in another lane										
Bus or truck in front of you										
Undesirable pavement conditions										

- Cooperation and competition in lane changing. Please describe your actions in two scenarios.



Scenario 1. You need to:

(a) change to the left-most lane;

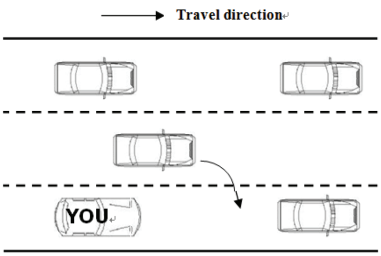
(b) change to the right- most lane;

Does any difference exist between normal and congested traffic situations?

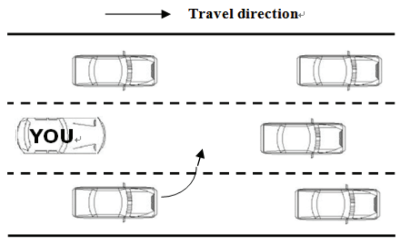
Scenario 2. Forced lane changing in front of you

(a) You are in the right-most lane and the other vehicle in the left lane is attempting to merge in front of you;

(b) You are in the median lane and the other vehicle is planning to merge in front of you.



(a)



(b)

Do you react differently in the following two lane changing scenarios? Is there any difference between normal and congested traffic situations?

4. Application 3: Overtaking behavior

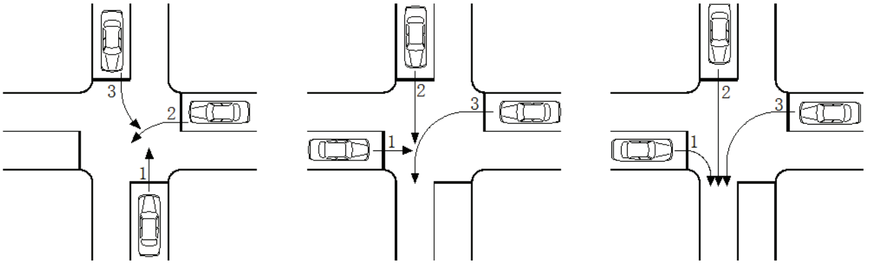
- What factors are most important to “overtaking”?
- What kind of overtaking behaviors you dislike?
- What do you think about ‘overtaking on the right side’?
- Please describe how you overtake a slowly moving vehicle.

5. Application 4: Reaction to signal

- What are you doing in the red phase when you are the first driver in the queue?
- What are your general reactions when you are the first driver in the queue as the signal turns green?
- What are your general reactions when you see the signal turning yellow?
- What factors can influence your reaction to traffic signal? Are you aware of some mistakes in your reaction to the signal?
- What is your attitude to a conflicting vehicle that is still remaining at the intersection at the beginning of a green phase?
- What is your opinion of the traffic signal design in Changsha?

6. Application 5: Knowledge of traffic rules

- Tell some rules related to priority. Are these rules important? Why?
- Identify the priority signs given in the questionnaire.
- Do you think some traffic rules are more important and others less important? Why?
- What offences do you often make? What is the reason in most of the time?
- What do you think about the punishment for your offences? Fair or not?
- If your offence is not recorded, do you re-disobey again?
- Please rank the priority of three vehicles in three scenarios:



(a) (b) (c)

7. Ending Questions

- How to improve the driver behavior in China?
- Are there any other issues related to driving you want to discuss?

Summary

Drivers, especially the drivers of private cars, are an important component of the road traffic system. The interactions between drivers and the interrelationship between driver and external traffic conditions determine the traffic performance to a certain extent. Driver behavior is influenced by the whole traffic environment, customs, and culture. Compared with developed countries, most developing countries have almost one century delay in traffic motorization. At present, these countries are at a crucial stage: transport demand and transport supply both have exploded in the past decades. The unbalance between supply and demand in traffic can't always be solved by introducing more transportation facilities or by extending the traffic infrastructure. There is evidence that improper driver behavior significantly contributes to the poor performance of roads and intersections in developing countries like China. An effective approach to mitigate the recurrent daily congestion can be the improvement of the driver behavior. However, it is still unclear how the improper driver behavior is developed by these drivers, and how their behavior can be changed to improve the traffic performance for a developing country, like China.

Traffic simulation models are an important tool for engineers to design traffic measures, as well as for researchers to study traffic problems. Nearly all current simulation models were developed in Western countries based on driver behavior as observed in those countries. Do these models suit the driver behavior in developing countries where the traffic infrastructure, culture and driving experience all distinctly differ from those in developed countries?

To clarify the above research questions, the research this dissertation takes China as the example of developing countries to identify the national driver behavior characteristics, to explore the main factors which can influence driver behavior, to find effective ways to improve driver behavior, to reveal the interaction effect between traffic performance and driver behavior, and to explore an effective way to calibrated simulation models based on local driver behavior.

The Netherlands, as a country with specific characteristics of developed countries, is selected to compare with China in this comparative study. In China, cities are suffering from higher traffic pressure compared with other regions. The management of signalized intersections is crucial to the performance of the whole road network in a city. Therefore, the data used in this study mainly collected from signalized intersections in urban areas. Since vehicles' movement should be analyzed at the individual level, the simulation model studied in this dissertation is

on a microscopic level. The different research approaches used in this study are listed as follows:

- Saturation flow investigation,
- Driver behavior questionnaire survey,
- Driver in-car test,
- Focus group discussion,
- Microscopic simulation model calibration.

Road traffic in China

Traffic is closely related to the social and economic development in a country. With the rapid economic development and fast urbanization process, traffic demand in China keeps increasing over the past 30 years. China has become the second largest motor vehicle country and the largest motor vehicle market since 2009. However, the average passenger car ownership was still at a low level: 34.5 cars per 1000 inhabitants in 2009 compared with the average number of 124.3 over the world. That means the high growth of passenger car ownership will still continue for quite a long time (22.06% in 2011). The high pressure on the transport infrastructure is especially visible in large Chinese cities.

In China, the number of licensed drivers keeps increasing at about an annual rate of 10%. In 2011, the number of drivers with less than 3 years driving experience is about 1/3 of the total driver population and 90% of drivers are younger than 50. There is evidence that the driving behavior of young drivers with limited driving experience is more risky than that of mature drivers. The high proportion of novel young drivers in China has influence on both the traffic performance and safety.

In the first half year of 2011, there were 25.6 million drivers with recorded traffic rule offences, namely 11.4% of the total driver population. The frequently recorded offences are speeding, illegal parking, driving on wrong lanes, disregarding signs and signals. In China, the number of fatal accidents per 1000 motor vehicles decreased from 1.4 in 2007 to 0.6 in 2011. Even though the statistics might not be completely comprehensive, the reported road fatalities are still rather high, compared with those in developed countries. Traffic accidents not only deteriorate traffic safety, but also worsen congestion. For instance, in June 2013 in Changsha – the capital of Hunan province in China -, 24% of the congestion was caused by traffic accidents.

Traffic rule offences are one of the main causes of traffic accidents in China. The main offences causing serious traffic accidents are speeding, ignoring priority rules, and no-license driving. In 2010, speeding and ignoring priority rules constituted 14% and 11.9% of the traffic fatalities respectively. In Changsha ignoring priority rules is the most dangerous behavior, since this kind of offence led to 25.19% of the accidents in March, 2012. Driving in wrong lanes, irregular lane changing, converse driving, and irregular overtaking totally resulted in 13.7% of traffic accidents. These kinds of offences are typical examples of improper driving behavior which is expected to be improved by strict traffic rule education and enforcement.

These statistics imply that Chinese traffic development status and drivers behavior both differ from those in developed countries. In China, there is great potential for improvement in driver behavior, traffic management and the related design. If an effective solution is developed for the transport problems in China, it can become a significant reference for other developing counties.

Traffic performance of signalized intersection

In Chinese cities, the poor performance of signalized intersections is one of the important causes for congestion in urban areas. Saturation flow characteristics, especially saturation flow rate, are most associated with the traffic performance at signalized intersections. In order to identify the factors which can significantly influence the performance of signalized intersections, a comparative study of the saturation flow characteristics was conducted in three Chinese and two Dutch cities.

The study results show that the saturation flow at Chinese intersections has the following characteristics: lower saturation flow rates (20–30% lower than Dutch peers), larger standard deviations in saturation flow rates and time headway, longer start lags, more vehicles experiencing start delay (between 4 and 6), all compared to the Dutch intersections.

The analysis identifies that the main cause for the low saturation flow rates at Chinese intersections is the poor driver behavior: the long and irregular time headways and sudden lane changing at the observed Chinese intersections. The long start lag in the beginning of the green phase at Chinese intersections is mainly brought by the presence of conflicting vehicles and pedestrians at the beginning of the green phase due to insufficient clearance time. Chinese drivers adapt themselves to the local conditions and behave differently from Dutch drivers, which result in a less efficient traffic system. The different driver behavior in China indicates that most microscopic simulation programs have to be adapted, calibrated and validated for Chinese situations.

Driver behavior questionnaire study made in China and the Netherlands

Human factors have an important influence on road traffic capacity and traffic performance. The Driving Behavior Questionnaire (DBQ) is a widely used instrument for measuring self-reported driving style in many countries. In 2013, an online questionnaire survey was carried out in China and the Netherlands to investigate the difference in driving behavior between these two countries and to explore the factors which can result in this difference.

Totally, 215 Chinese drivers and 175 Dutch drivers filled in an online questionnaire from January to June in 2013. Results of the statistical analysis show that self-reported driving behavior in China and the Netherlands are significantly different from each other. Chinese respondents reported much more offences and accidents than the Dutch peers. An aggressive score is introduced to evaluate driving style based on the answers on 30 items related to driving behavior. Chinese respondents got much higher aggressive scores and showed much larger variations in almost every item in the questionnaire than the Dutch peers. The large variations in the DBQ answers account for the remarkable heterogeneity of the traffic flow in

China. Furthermore, a distinct difference has been found in the knowledge of priority rules between the two countries. In Chinese data sample, the percentages of respondents who stated they knew the priority signs given in the questionnaire were about 75 for road side signs and only 32 for the pavement sign. The corresponding value was larger than 95 in Dutch data sample. For some given scenarios, fewer Chinese respondents provided priority to the conflicting pedestrians and vehicles than the Dutch peers. Subsequently, the influence on driving in practice will be that drivers are always uncertain and hesitative, which makes the traffic flows inefficient.

A factor analysis of DBQ demonstrates that the aggressive score is correlated with self/others estimated driving style in both two countries. The aggressive score of the Dutch respondents has a close relationship with accident involvement. Independent sample nonparametric tests reveal that gender and occupation both have a significant correlation with driving behavior in the Dutch sample, but both don't show a strong relationship with driving style in the Chinese sample.

The survey results also indicate that Chinese drivers do not know they drive in an aggressive way compared with Dutch drivers. Traffic rules (e.g. priority) and their application in China might not be as standardized as in the European countries. Thus, the self-reported driver behaviors present significant differences in the two countries.

Specific study based on in-car tests

The questionnaire survey reveals the distinct difference in self-reported driver behavior between the Netherlands and China. It is important to verify the questionnaire answers in reality through in-car tests, because the questionnaire survey only reveals what the respondents considered their own driver behavior to be. In this study, the in-car tests were made for 30 drivers with their own cars in May and June in 2013 in Changsha. The participants filled in the same DBQ prior to or after in the in-car test. Three cameras were installed in the test cars: one camera was used to record the traffic situation in front of the car, the second camera was used to record the face of the driver, and the third camera was fixed behind the driver to record the operation of the driver. A GPS receiver was fixed on the top of the car to record the speed and the coordinates with 1Hz frequency. Acceleration/speed profiles in driving could be registered. Every participant drove for about 30 minutes in downtown Changsha. The main findings obtained from in-car tests are:

- The driver behavior in reality is consistent with the answers in questionnaire on the whole. The DBQ aggressive scores have been verified through in-car tests. Drivers with higher DBQ aggressive scores behaved more aggressively during in-car tests.
- Drivers' acceleration/speed characteristics are quite different from each other and are classified according to the collected data.
- Gender was found to be significantly relevant to driver behavior. The links between driving behavior and driver occupancy (professionals vs. non-professionals) and vehicle gear types (automatic vs. manual) were relatively weak.
- Drivers' driving style is quite stable when several tests are made, as long as the traffic conditions and driving tasks do not vary too much.

- The traffic density was negatively associated with the drivers' acceleration/deceleration and lane changing behavior.
- Overtaking on the right side and long time driving on the left-most lane are quite common driving behavior.

Focus group discussion

Focus group discussions assist in understanding participants' attitudes and opinions of a certain issue. In this study, six focus groups were organized to investigate Chinese drivers' attitudes to driving, intended actions, their preferences, and driving habits in different traffic situations.

Most participants explained that the knowledge of traffic rules learned in the driver license courses fades away in the daily driving experience, rather than being reinforced. Therefore, most drivers aren't certain about what other drivers will do and they have to behave carefully. This driving attitude can't prevent or solve conflicts, while it decreases traffic efficiency in practice. Most participants stated that the rule with regard to the yellow light is quite ambiguous and they don't know the appropriate reaction when they are the first driver in the queue to a yellow light. This uncertainty will not only reduce the capacity of a signalized intersection, but also increase the risk of accidents.

The participants confirmed that traffic situations (like congestion, long delays) have an important influence on driver behavior. The personal mood, such as hurry, irritation and impatience, is an important determinant of the driving behavior.

Participants described some special features in lane changing and overtaking. First of all, lane changing to a left lane requires a shorter gap than the movement to a right lane. Courtesy yielding is more likely provided for cars moving to the right lane, rather than for car changing to the left lane. Since many drivers prefer to drive in the left lane for long time, overtaking on the right side is very common in reality. Accepted gaps for lane changing depend on the traffic situation and are often achieved by a forced lane change under a dense traffic condition.

The results of focus group discussion show that there are lots of opportunities for improving driving behavior in Chinese cities. This can be realized by stronger enforcement of traffic rules, more attention to safe driving attitudes in driving training and testing, and more education of traffic rules to all of road users.

Microscopic simulation model calibration based on driver behavior survey results

Before being used for traffic analysis in practice, simulation programs should be calibrated to reproduce the traffic characteristics. In most cases, measured volumes, travel times and queues are used to calibrate simulation models, rather than detailed driving characteristics such as speed and acceleration patterns. However, the parameters related to driving characteristics determine some specific simulation results, like saturation flow rates and vehicular emissions, to a great extent.

In this dissertation, a microscopic simulation model (VISSIM) is calibrated with GPS data collected by in-car tests in Changsha and measured saturation flow rates. The speed and acceleration profiles deduced from real data are significantly different from those calculated by a simulation model with default parameter settings.

After a sensitivity analysis, driving behavior parameters which are strongly related to simulation outputs of speed and acceleration were determined. The targets for the calibration are speed distribution, acceleration and deceleration distribution, and saturation flow rates. Travel times are not used as a calibration target, because these are determined directly by the desired speeds, the traffic control, and saturation flow rates.

The observed accelerations could not be directly used to determine the desired acceleration function, because when the vehicle is in car-following state, the driver often cannot execute the desired acceleration. The calibration of desired speed is confronted with the same question. A censor method is proposed to calibrate the desired speed distribution and desired acceleration function with the GPS data. The parameters in car following model are pair wise calibrated for saturation flow rates. The iteration shows that this calibration process is quite robust. The model validation shows that the calibrated model can simulate drivers' behavior quite well under different traffic conditions. Four driving types classified in the DBQ and in-car tests have been calibrated individually. Distinct differences are found in desired speed and maximum desired acceleration/deceleration. The category of driving type is expected to be useful in model calibration in the future. Then the calibration work can be simplified to determine the proportion of every driving type.

GPS probe vehicles are a convenient data source and can reveal different driver behavior of the same driver in different traffic situations. This study also reveals that simulation programs have limitations in some of the driver behavior features. For example, it is difficult to reproduce the variation of driver behavior with the change of driving task, personal mood, and traffic conditions.

Implication for simulation model improvement

Traffic simulation models have been applied in traffic planning, evaluation and design. Most of these models are based on relatively ideal driver behavior. This study shows what model modifications and calibration are needed to accord with the driver behavior in practice.

In simulation programs, it is necessary to distinguish different driving types, such as an aggressive or a conservative style – even though the same driver can switch between these styles. The distribution over conservative and aggressive drivers should depend on the traffic situation. This study also shows that simulation models developed in Western countries should be adapted to Chinese driving behavior, especially the difference in saturation flow, lane changing, and priority giving. Also the influence of traffic conditions on driver behavior should be considered. In the present models, there is no clear function in which the traffic conditions can influence the driver behavior. Therefore, it might be necessary to define an external function to link traffic conditions with a common driver behavior model.

Samenvatting

Bestuurders van personenauto's zijn een belangrijk onderdeel van het wegverkeersysteem. De interactie tussen bestuurders onderling en tussen bestuurder en externe verkeersomstandigheden bepalen tot op zekere hoogte de verkeersprestaties. Rijgedrag wordt beïnvloed door de verkeersomstandigheden, gewoonten en cultuur. In vergelijking met ontwikkelde landen, lopen de meeste ontwikkelingslanden bijna een eeuw achter in de motorisering van het verkeer. Op dit moment zijn deze landen in een cruciale fase; de vraag en het aanbod van vervoer zijn in het afgelopen decennia enorm gestegen. De onbalans tussen vraag en aanbod in het verkeer kan niet altijd worden opgelost door de invoering van meer vervoersvoorzieningen of door uitbreiding van de verkeersinfrastructuur. Er is bewijs dat onjuist rijgedrag, in een ontwikkelingsland als China, aanzienlijk bijdraagt aan de slechte verkeersprestaties op wegen en kruispunten. Een effectieve aanpak om de steeds terugkerende dagelijkse congestie te beperken, kan de verbetering van het rijgedrag zijn. Het is echter nog onduidelijk hoe het onjuiste rijgedrag van de bestuurder is ontstaan en hoe het gedrag kan worden veranderd om de verkeersprestaties voor een ontwikkelingsland, zoals China, te verbeteren.

Verkeerssimulatiemodellen zijn een belangrijk instrument voor ingenieurs om verkeersmaatregelen te ontwerpen, evenals voor onderzoekers om verkeersproblemen te bestuderen. Bijna alle huidige simulatiemodellen zijn ontwikkeld in westerse landen, gebaseerd op het rijgedrag zoals waargenomen in die landen. De vraag is nu: passen deze modellen ook bij het rijgedrag van bestuurders in ontwikkelingslanden waar de verkeersinfrastructuur, -cultuur en rijervaring allemaal duidelijk verschillen van die in de ontwikkelde landen?

De belangrijkste doelstellingen van dit proefschrift zijn duidelijkheid te verkrijgen met betrekking tot de bovenstaande onderzoeksvragen: (1) om kenmerken van het nationale rijgedrag van de bestuurders te vinden, (2) om de belangrijkste factoren in kaart te brengen die het gedrag van de bestuurder kunnen beïnvloeden, (3) om effectieve manieren te zoeken om het gedrag van de bestuurder te verbeteren, (4) om het interactie-effect tussen de verkeersprestaties en het rijgedrag te vinden en (5) om een effectieve manier te ontwikkelen om simulatiemodellen te kalibreren op basis van rijgedrag van de bestuurder in een ontwikkelingsland.

China en Nederland zijn twee landen die specifieke kenmerken hebben van een respectievelijk ontwikkelings- en ontwikkeld land. Deze landen zijn geselecteerd voor de vergelijkende studie. Steden in China lijden aan een hogere verkeersdruk dan in andere regio's in het land en het beheer van de geregelde kruispunten is van cruciaal belang voor de prestaties van het gehele wegennet in een stad. Daarom is de verzameling van gegevens in dit onderzoek vooral gericht op geregelde kruispunten in stedelijke gebieden. Aangezien de beweging van voertuigen moet worden geanalyseerd op individueel niveau, is het simulatiemodel dat bestudeerd wordt in dit proefschrift, op een microscopisch niveau. De aanpak van het onderzoek voor deze studie, is als volgt:

- Onderzoek naar de capaciteit van rijstroken (saturation flow),
- Enquête over Rijgedrag,
- Testritten in een auto (in-car tests),
- Focusgroepsdiscussies (focusgroups),
- Kalibratie van een microscopisch simulatiemodel.

Wegverkeer in China

Verkeer wordt nauw gerelateerd aan de sociale en economische ontwikkeling in een land. Door de snelle economische ontwikkeling en snelle verstedelijking bleef de verkeersvraag in China stijgen in de afgelopen 30 jaar. China is uitgegroeid tot het een na grootste motorvoertuigen land van de wereld en heeft de grootste markt voor motorvoertuigen sinds 2009. Het personenautobezit is echter nog steeds erg laag: 34,5 auto's per 1000 inwoners in 2009 vergeleken met het gemiddelde aantal van 124,3 over de hele wereld. Dat betekent dat de hoge groei van personenautobezit zal doorgaan voor een behoorlijk lange tijd (22,06% groei in 2011). De hoge druk op vervoersinfrastructuur in China is vooral zichtbaar op de stedelijke wegen in grote steden.

In China blijft het aantal bestuurders met rijbewijs steeds groeien, jaarlijks met 10%. In 2011 is het aantal bestuurders met minder dan 3 jaar rijervaring ongeveer 1/3 van de totale bestuurdersbevolking; 90% van de bestuurders is jonger dan 50 jaar. Er is aangetoond dat het rijgedrag van jonge bestuurders met weinig rijervaring riskanter is dan dat van ervaren bestuurders. Dit heeft zowel invloed op de verkeersprestaties als de veiligheid.

In het eerste halfjaar van 2011 waren er 25,6 miljoen bestuurders die zijn beboet voor het overtreden van de verkeersregels, dit is 11,4% van de totale bestuurdersbevolking. De meest geregistreerde overtredingen zijn: te hard rijden, fout parkeren en rijden op verkeerde rijstroken, zonder rekening te houden verkeerstekens en -signalen. In China daalde het aantal dodelijke ongevallen van 1,4 per 1.000 motorvoertuigen in 2007 tot 0,6 in 2011. De statistieken zijn wellicht niet volledig . De gerapporteerde verkeersdoden zijn in elk geval nog steeds vrij hoog. Verkeersongevallen verslechteren niet alleen de verkeersveiligheid, maar verergeren ook congestie. Als voorbeeld, was in juni 2013 in Changsha - de hoofdstad van de provincie Hunan in China -, 24% van de congestie te wijten aan verkeersongevallen.

Verkeersovertredingen zijn een van de belangrijkste oorzaken van verkeersongevallen in China. De belangrijkste overtredingen die ernstige verkeersongevallen veroorzaken zijn te hard rijden, het negeren van voorrangsregels, en het zonder rijbewijs rijden. In 2010 vormden het te hard rijden en het negeren van voorrangsregels respectievelijk 14% en 11,9% van de verkeersdoden. In Changsha is bijvoorbeeld het negeren van voorrangsregels het meest risicovolle rijgedrag, aangezien deze overtredingen hebben geleid tot 25,19% van de ongevallen in maart 2012. Het kiezen van de verkeerde rijstrook, irregulier wisselen van rijstrook, tegen het verkeer in rijden, en irregulier inhalen resulteerde in 13,7% van de verkeersongevallen. Dit soort overtredingen zijn typische voorbeelden van onjuist rijgedrag dat naar verwachting wordt verbeterd door betere educatie van de verkeersregels, en strengere handhaving.

Deze statistieken laten zien dat de Chinese verkeerstoestand en rijgedrag beide verschillen van die in ontwikkelde landen. In China zijn er grote kansen voor verbeteringen in het gedrag van de bestuurder, verkeersmanagement en het ontwerp van infrastructuur. Als een effectieve oplossing wordt ontwikkeld voor de vervoers- en verkeersproblemen in China, kan het een belangrijke voorbeeldfunctie krijgen voor andere ontwikkelende landen.

Verkeersprestatie van geregelde kruispunten

In Chinese steden is de slechte verkeersprestatie van geregelde kruispunten een van de oorzaken voor congestie in stedelijke gebieden. De karakteristieken van de capaciteit van rijstroken (saturation flow) bepalen voor een groot deel de verkeersprestaties van geregelde kruispunten. Om de factoren die aanzienlijk invloed kunnen hebben op de prestaties van geregelde kruispunten, te identificeren, werd een vergelijkende studie uitgevoerd naar de karakteristieken van de rijstrookcapaciteiten in drie Chinese en twee Nederlandse steden.

De studie resultaten tonen aan dat de rijstrookcapaciteit bij Chinese kruispunten de volgende kenmerken heeft: lagere capaciteit (20-30% lager dan in Nederland), grotere standaarddeviaties in rijstrookcapaciteit en volgtijd, langere startvertragingen (tussen 4 en 6 seconden), dit alles in vergelijking tot Nederlandse kruispunten.

De analyse laat zien dat de belangrijkste oorzaak voor de lage rijstrookcapaciteit op de Chinese kruispunten het rijgedrag van de bestuurder is: de betrekkelijke lange en onregelmatige volgtijden en de plotselinge veranderingen van rijstrook op de waargenomen Chinese kruispunten worden als belangrijke oorzaken gezien. De lange startvertraging in het begin van de groenfase bij Chinese kruispunten wordt voornamelijk veroorzaakt door de aanwezigheid van conflicterende voertuigen en voetgangers aan het begin van de groene fase door gebrek aan voldoende ontruimingstijd. Chinese bestuurders passen zich aan aan de lokale omstandigheden en gedragen zich daardoor anders dan Nederlandse bestuurders. Dit resulteert in een minder efficiënt verkeerssysteem. Het blijkt tevens dat het rijgedrag in China er de oorzaak van is dat de meeste microscopische simulatie programma's moeten worden aangepast, gekalibreerd en gevalideerd voor Chinese situaties.

Enquête rijgedrag uitgevoerd in China en Nederland

Menselijke factoren hebben een belangrijke invloed op de capaciteit van het wegverkeer en de verkeersprestaties. De vragenlijst over rijgedrag (Driver Behavior Questionnaire, DBQ) is een veelgebruikt instrument voor het meten van zelf-gerapporteerde rijstijl. In 2013 werden twee online enquêtes uitgevoerd, één in China en één in Nederland, om het verschil in rijgedrag tussen deze twee landen te onderzoeken en de factoren te verkennen die het gedrag van de bestuurder kunnen beïnvloeden. De inhoud van de vragen was voor beide landen identiek.

In totaal hebben 215 Chinese automobilisten en 175 Nederlandse automobilisten een online vragenlijst ingevuld, tussen januari en juni 2013. Uit de resultaten van de statistische analyse blijkt dat het zelf-gerapporteerde rijgedrag in China en Nederland significant van elkaar verschilt. Chinese respondenten begaan veel meer overtredingen en maken meer ongevallen dan de Nederlandse respondenten. Een agressiviteitsscore is ingevoerd om de rijstijl te evalueren met betrekking tot agressief rijgedrag gebaseerd op de antwoorden op 30 vragen. Chinese respondenten kregen veel hogere agressiviteitsscores en toonden veel grotere variaties in bijna elk item in de vragenlijst dan de Nederlandse respondenten. De grote variaties in de antwoorden van de DBQ worden door de Chinese respondenten toegeschreven aan de heterogeniteit van de verkeersstromen in China. Verder is een duidelijk verschil gevonden in de kennis van de voorrangsregels tussen de twee landen. Van de Chinese respondenten verklaarden ongeveer 75% de betekenis te kennen voor de verkeersborden langs de weg en slechts 32% de tekens te kennen die op het wegdek worden aangebracht. Het overeenkomstige percentage voor de Nederlandse data was groter dan 95%. Voor een aantal gegeven scenario's, verleenden minder Chinese respondenten voorrang aan de conflicterende voetgangers en voertuigen dan de Nederlandse respondenten. De invloed op het rijden in de praktijk is dat de Chinese bestuurders veel onzekerder zijn en daardoor aarzelen, waardoor de verkeersstromen inefficiënter worden.

Factoranalyse toont aan dat de agressiviteitsscore is gecorreleerd met de door zichzelf/anderen geschatte rijstijl in de twee landen; de agressiviteitsscore van de Nederlandse respondenten heeft een nauwe relatie met betrokkenheid bij ongevallen. Uit een onafhankelijke niet-parametrische test blijkt dat geslacht en beroep beide een significante correlatie hebben met het rijgedrag in de Nederlandse steekproef, maar deze relatie wordt niet gevonden in de Chinese steekproef.

De onderzoeksresultaten ondersteunen de conclusie dat de Chinese bestuurders rijden zonder zich volledig bewust te zijn van hun rijstijl. Verkeersregels (b.v. voorrangsregels) en hun toepassing zijn in China wellicht niet zo gestandaardiseerd als in de Europese landen. Er is dus een significant verschil in zelf-gerapporteerd rijgedrag tussen beide landen.

Specifieke studie gebaseerd op test ritten

Uit de vragenlijst, gebruikt in dit proefschrift, blijkt dat er een verschil is in zelf-gerapporteerd rijgedrag tussen Nederland en China. Het is belangrijk om de antwoorden op de vragenlijst te verifiëren door testritten met auto’s, omdat uit de enquête alleen blijkt wat de respondenten zelf aangeven over hun eigen rijgedrag. In dit onderzoek werden de testritten uitgevoerd voor 30 bestuurders met hun eigen auto in mei en juni 2013 in Changsha. De deelnemers vulden dezelfde vragenlijst vóór of na de testrit in. Drie camera's werden in de testauto geïnstalleerd: een camera werd gebruikt om de verkeerssituatie vóór de auto waar te nemen, de tweede camera werd gebruikt om het gezicht van de bestuurder te filmen en de derde camera werd achter de bestuurder bevestigd om zo handelingen van de bestuurder te filmen. Een GPS ontvanger was bevestigd aan de bovenkant van de auto om de snelheid en de coördinaten met

1Hz frequentie op te nemen. Acceleratie / snelheidsprofielen tijdens het rijden konden hierdoor worden geregistreerd. Iedere deelnemer reed voor ongeveer 30 minuten in het centrum van Changsha. De belangrijkste bevindingen verkregen uit de testritten zijn:

- Het rijgedrag in werkelijkheid komt goed overeen met de antwoorden op de vragenlijst. De agressiviteitsscores zijn geverifieerd door middel van de testritten. Bestuurders met een hogere agressiviteitsscore gedroegen zich agressiever tijdens de testritten.
- Acceleratie- en snelheidspatronen van bestuurders zijn onderling heel verschillend en zijn geclassificeerd aan de hand van de verzamelde gegevens.
- Geslacht bleek significant relevant te zijn voor het rijgedrag van de automobilisten. De verbanden tussen rijeigenschappen en het beroep van de bestuurder (al dan niet beroepschauffeur) en voertuig transmissietype (automatisch versus handgeschakeld) waren relatief zwak.
- De rijstijl van bestuurders is vrij stabiel wanneer meerdere ritten gemaakt worden, zolang het verkeer en de rijomstandigheden niet te veel variëren.
- De verkeersdichtheid heeft een negatieve samenhang met de acceleratie/ deceleratie van bestuurders en rijstrookwisselgedrag.
- Inhalen aan de rechterkant en het rijden voor lange tijd op de meest linkse rijstrook zijn heel algemeen rijgedrag.

Focusgroep onderzoek naar de mening van bestuurders over het rijden in China

Focusgroep discussies helpen bij het begrijpen van het rijgedrag en kunnen de meningen van deelnemers over bepaalde kwesties in kaart brengen. In deze studie werden zes focusgroepen georganiseerd om de meningen van Chinese bestuurders te onderzoeken, met betrekking tot het rijden, voorgenomen acties, hun voorkeuren en het rijgedrag in verschillende verkeerssituaties.

De meeste deelnemers legden uit dat de kennis van de geleerde verkeersregels tijdens het behalen van het rijbewijs verdwijnt in de praktijk van het dagelijkse rijden. Daarom zijn de meeste automobilisten niet zeker over wat andere bestuurders zullen doen en zullen zij zich daarom oplettend moeten gedragen. Deze houding kan geen conflicten voorkomen of oplossen, terwijl het wel de efficiëntie van het verkeer in de praktijk vermindert. Deelnemers verklaren verder dat de regel met betrekking tot het gele licht bij een verkeerslicht nogal dubbelzinnig is en ze geven aan dat ze niet weten hoe ze moeten reageren als ze als eerste automobilist het gele licht zien. Deze onzekerheid zal niet alleen de capaciteit van een geregeld kruispunt verminderen, maar ook het risico op ongevallen verhogen.

De deelnemers bevestigden dat de rijomstandigheden (zoals files, lange wachttijden) een belangrijke invloed hebben op het rijgedrag. De persoonlijke omstandigheden, zoals haast, irritatie en ongeduld, beïnvloeden ook in een belangrijke mate het rijgedrag.

Deelnemers beschreven een aantal speciale functies in het wisselen van rijstroken en het inhalen. Allereerst vereist een wisseling van rijstrook naar een linkerbaan een korter hiaat dan de wisseling naar een rechterbaan. Ruimte geven om van rijstrook te wisselen uit hoffelijkheid komt vaker voor wanneer automobilisten willen wisselen naar de rechter rijstrook dan wanneer ze willen wisselen naar de linker rijstrook. Aangezien veel automobilisten liever voor lange tijd met de auto op de linker rijstrook rijden, wordt er vaak rechts ingehaald. Geaccepteerde hiaten voor het wisselen van rijstrook zijn afhankelijk van de verkeerssituatie en worden vaak bereikt door een geforceerde rijstrookwisseling in drukke verkeersomstandigheden.

Uit de resultaten van de focusgroep discussie blijkt dat er mogelijkheden zijn voor het verbeteren van het rijgedrag in Chinese steden. Dit kan gerealiseerd worden door een striktere handhaving van de verkeersregels, meer aandacht voor veilig rijden in rijopleidingen en meer onderwijs van de verkeersregels voor alle weggebruikers.

Kalibratie van een microscopisch simulatiemodel op basis van de onderzoeksresultaten over het rijgedrag

De simulatie programma's, gebruikt voor praktische verkeersanalyses, moeten worden gekalibreerd om de juiste verkeerskarakteristieken te reproduceren. In de meeste studies worden de gemeten intensiteiten, reistijden en wachtrijen gebruikt om simulatiemodellen te kalibreren, in plaats van gedetailleerde rijeigenschappen zoals snelheids- en acceleratiepatronen. Echter, de parameters voor deze rijpatronen bepalen grotendeels een aantal gedetailleerde simulatieresultaten, zoals rijstrookcapaciteit en voertuigemissies.

In deze dissertatie wordt een microscopisch simulatiemodel (VISSIM) gekalibreerd met GPS-gegevens die bij testritten in Changsha zijn verzameld. De snelheids- en versnellingsprofielen verkregen uit data blijken significante verschillen te tonen met de profielen die worden berekend door een simulatiemodel met standaard parameterinstellingen.

Na de gevoeligheidsanalyse werden de rijgedrag parameters die sterk gerelateerd zijn aan gesimuleerde snelheid en acceleratie, bepaald. De doelstellingen voor de kalibratie zijn: realistische statistische verdelingen van snelheden, versnelling en vertraging, rijstrookcapaciteit. Reistijden worden niet gebruikt als kalibratiedoel, omdat reistijden worden bepaald door de gewenste snelheid, de instelling van de verkeerslichten, en rijstrookcapaciteiten.

De waargenomen acceleraties kunnen niet direct worden gebruikt om de maximale, gemiddelde en minimale gewenste acceleratie functies te bepalen, omdat wanneer een voertuig een voorganger volgt, de bestuurder vaak niet de gewenste acceleratie kan realiseren. Voor het vaststellen van de gewenste snelheden geldt hetzelfde. Een censor methode wordt voorgesteld om de gewenste versnellingsverdeling af te leiden uit met GPS gemeten acceleraties. De gewenste versnellingen en vertragingen zijn in VISSIM gekalibreerd met behulp van de gecensureerde waarnemingen, wat resulteerde in realistische gesimuleerde acceleratie- en snelheidspatronen. De parameters van het voertuig-volgmodel zijn paarsgewijs gekalibreerd met de rijstrookcapaciteit als optimalisatiecriterium. Een validatie van het gekalibreerde simulatiemodel laat zien, dat het model voertuiggedrag onder verschillende verkeersomstandigheden goed simuleert

De kalibratie is uitgevoerd voor de vier klassen van bestuurders die in het DBQ onderzoek zijn gevonden. Duidelijke verschillen blijken te bestaan in de maximale gewenste versnelling / remvertraging en wenssnelheid. De gevonden indeling van bestuurders in de vier klassen zal naar verwachting nuttig zijn voor toekomstige modelkalibratie. De kalibratie kan vereenvoudigd worden tot het bepalen van de samenstelling van het verkeer met betrekking tot de vier klassen.

Voertuigen uitgerust met GPS zijn een geschikte gegevensbron, waarmee verschillend rijgedrag van dezelfde bestuurder in verschillende verkeerssituaties in kaart kan worden gebracht. Deze studie toont ook aan dat de simulatie programma's beperkingen hebben in een aantal aspecten van verkeersgedrag. Het is bijvoorbeeld moeilijk om de variatie van het rijgedrag met de verandering van rij-taken, persoonlijke omstandigheden en verkeersomstandigheden inzichtelijk te krijgen.

Consequenties voor de verbeteringen voor simulatie modellen

Verkeerssimulatiemodellen zijn ontwikkeld voor en toegepast in verkeersplanning, -evaluatie en -ontwerp. De meeste van deze modellen zijn gebaseerd op relatief ideaal rijgedrag. Deze studie toont aan welke modelwijzigingen en kalibratie nodig zijn om overeenstemming te krijgen met het rijgedrag in de praktijk.

Het is noodzakelijk om in simulatieprogramma's verschillende soorten automobilisten te onderscheiden, zoals agressieve of conservatieve bestuurders – zelfs wanneer dezelfde bestuurder niet steeds in dezelfde categorieën valt. De verdeling over de conservatieve en agressieve bestuurders moet afhangen van de verkeerssituatie. Deze studie toont ook aan dat simulatiemodellen, ontwikkeld voor westerse landen, moeten worden aangepast voor de Chinese rijomstandigheden. Er moet vooral rekening gehouden worden met het verschil in rijstrookcapaciteit, het wisselen van rijstrook, en het voorrang geven. Ook de invloed van de verkeerssituatie op het rijgedrag moet worden meegenomen. In de huidige modellen is er geen duidelijk mechanisme waarbij de verkeerssituatie het rijgedrag kan beïnvloeden. Daarom kan het nodig zijn om een externe functie, met verkeersomstandigheden gerelateerde parameters, te koppelen aan een algemeen rijgedrag model.

(Dutch translation by Elisabeth van der Horst)

概述 (Summary in Chinese)

驾驶人，尤其是私家车驾驶人是道路交通系统的一个重要组成部分。交通性能在一定程度上取决于驾驶人之间的互动，以及驾驶人与交通环境间的相互影响。驾驶行为受整个交通环境、习俗和文化背景的影响。与发达国家相比，大多数发展中国家的交通机动化发展滞后约一个世纪。这些国家目前正处于一个交通发展的关键阶段：交通需求与交通供给在过去的几十年都得到了井喷式发展，而交通供小于求的矛盾不能永远通过增加交通工具或扩建交通基础设施来解决。有研究表明，不良的驾驶行为是许多发展中国家（如：中国）城市道路和交叉口交通状况恶化的一个重要原因。缓解日常交通拥堵问题的一个有效途径是改善开车人的驾驶行为。在诸如中国这样的发展中国家，开车人的不良驾驶行为是如何形成的？如何通过改善驾驶行为来提高交通效率？这些问题还没有明确答案。

交通仿真模型是技术人员制定交通措施、科研人员研究交通问题的一个重要工具。几乎所有目前流行的仿真模型都是由西方发达国家研发的。而这些模型的研发又是基于对本国驾驶行为的观察。在交通设施、文化背景和驾驶经验迥异的发展中国家，这些仿真模型还能适用吗？

为了解答以上问题，本文以中国为发展中国家的代表，调查驾驶行为特征，明确影响驾驶行为的主要因素，探求改善驾驶行为的有效途径，研究交通状态与驾驶行为之间的相互影响，并寻求基于本地驾驶行为标定仿真模型的有效方法。

荷兰，一个具有发达国家典型特征的国家，在此被选作和中国进行对比研究的对象。当前，中国的城市相较其他地区承受更大的交通压力。信号交叉口的管理是整个城市路网交通运行良好与否的关键。本研究的数据主要采集于城市信号控制交叉口。因为车辆的运动需具体到个体，本文研究的仿真模型是微观层面的。本文采用到以下研究方法：

- 饱和车流调查
- 驾驶行为问卷调查
- 实际驾驶调查
- 焦点小组讨论
- 微观仿真模型标定

中国道路交通概况

交通与一个国家的社会经济发展密切相关。随着经济的快速发展、城市化进程的加速，中国的交通需求在过去的30年间持续增长。2009年，中国成为世界第二大汽车保有国和第一大汽车市场。然而，2009年中国的千人小客车保有量（34.5小客车/千人）仍然远低于世界平均值（124.3小客车/千人）。这意味着在未来相当长的时间中国小客车的保有量还将高速增长（2011年为22.06%）。由此给交通设施带来的巨大压力已体现在中国的大城市中。

中国有驾驶执照的人数年增长率约为10%。在2011年，驾龄低于3年的驾驶人占总驾驶人的1/3，90%的驾驶人年龄不足50。有研究表明缺乏经验的年轻人比经验丰富的司机开车更加冒险。年轻新手在中国驾驶人中占较高的比例，这对交通性能和交通安全均具有深远影响。

在2011上半年， 中国有25.6万驾驶人有交通违章记录在案，这占总驾驶人的11.4%。最常见的交通违章是超速、违法停车、不按规定车道行驶、不按交通标志行驶、不按交通信号灯行驶。在中国，每千人交通事故死亡人数由2007年的1.4下降到2011年的0.6。即便统计数据有可能不全面，记录在案的交通事故死亡人数与发达国家相比仍然相当高。交通事故不但恶化交通安全，而且还加重交通拥堵。例如，在2013年6月，长沙（中国湖南省的省会）24%的交通拥堵是由交通事故造成的。

在中国，交通违章是交通事故的主要诱因。导致严重交通事故的违章行为主要有超速、违反优先权规定和无证驾驶。在2010年，超速和违反优先权规定分别导致了14%和11.9%有人员伤亡的严重交通事故。在2012年3月的长沙市区，违反优先权规定导致了25.19%的交通事故，成为一种最危险的驾驶行为。不按规定车道行驶、违章变道、逆向行车和违章超车这四种违章行为总共导致了13.7%的交通事故。这些违章属于典型的不良驾驶习惯，并且可以通过加强交通规则的教育和加大交通执法力度得到改善。

这些统计数据说明中国交通发展状况和驾驶人的行为均不同于发达国家。中国在驾驶行为、交通管理和相关的设计方面都存在巨大的改善空间。如果中国能找到一套解决交通问题的有效方案，这将为其他发展中国家提供一个有益的借鉴。

交叉口的交通性能

在一些中国城市，运行不佳的信号交叉口是市区交通堵塞的一个重要原因。信号交叉口饱和车流的特征（尤其是饱和流率）与交叉口的运行状态密切相关。为了确定影响信号交叉口性能的主要因素，本文在中国和荷兰两国进行了饱和车流对比研究。

相比荷兰，中国交叉口的饱和车流具有以下特征：低饱和流率（比荷兰低20~30%），饱和流率和车头时距均具有较大的标准偏差，启动延误影响更多的车（4~6辆车）。

分析发现中国交叉口饱和流率低的一个主要原因是不良驾驶行为：过长而不均匀的车头时距和突然变更车道。中国交叉口绿灯开启后启动延误过长，其主要原因是不充分的清空时间。上个周期的车辆和行人在下个绿灯开启时还滞留在冲突区。中国驾驶人适应当地交通条件，并形成与荷兰驾驶人不同的行为习惯，但不良的驾驶行为降低交通系统的运行效率。中国驾驶人的不同驾驶行为预示大多数仿真模型应该针对中国的国情进行调整、参数标定和验证。

中荷驾驶行为问卷调查

人的因素对道路通行能力和运行状况有着重要影响。驾驶行为问卷调查（DBQ）是根据自我填答调查驾驶行为，这一方式已在许多国家得到广泛采用。在2013年，本文作者所属研究团队在中国和荷兰同时进行了驾驶行为在线问卷调查，以对比研究两国的驾驶行为差异，并探究造成这些差异的原因。

2013年1~6月，此次调查在中国和荷兰分别收到215份和175份有效答卷。统计分析表明两国自陈的驾驶行为存在显著差异。中国参与者比荷兰参与者有明显多的违章记录和交通事故。本文将冒进指数引入统计分析，并根据参与者对问卷中30个与驾驶行为有关问题的回答评价其驾驶风格。中国参与者几乎每道题的冒进指数和标准偏差均比荷兰参与者高得多。对问卷作答过于离散也正好解释了交通流异质现象，即在中国观察到的交通流不均匀。两国参与者对于交通优先权知识的掌握也存在明显差异。中国参与者表示知道所列路侧交通标志和路面交通标识的比例分别为75%和32%。而荷兰参与者这两

个比例均超过了95%。针对所给的交通冲突例子，较少的中国参与者愿意给有冲突的行人和车辆让行。这在实际驾驶中则表现为驾驶人总是犹犹豫豫和不确定，从而降低了通行效率。

对答卷的因子分析揭示两个国家的冒进指数均与自我评估/他人评估的驾驶风格相关。荷兰参与者的冒进指数与交通事故的发生次数密切相关。独立样本的非参数检验证明荷兰参与者的性别和职业均与驾驶行为显著相关。但这一相关性在中国的数据样本中不明显。

调查表明中国驾驶人并没意识到自己与荷兰人相比开车很冒进。交通规则（比如优先权规则）在中国的执行可能并没有达到欧洲国家标准化水平。因此，两国自陈的驾驶行为存在显著差异。

实际驾驶调查

问卷调查揭示出中荷两国自陈驾驶行为存在显著差异。但问卷调查只是参与者自陈的驾驶行为，因此很有必要对问卷调查的结果通过实际驾驶进行验证。2013年5~6月，在长沙有30名驾驶人通过驾驶自己的小客车参与了驾驶调查。参与者在调查前或调查后对同样的问卷进行作答。调查中每一辆车都安装了三台摄像机：一台用来记录车辆前方的交通状况，一台用来记录驾驶人的面部表情，另一台固定在驾驶人后面用来记录其操作动作。一台固定在汽车的顶部GPS接收机以1HZ的频率记录车辆的速度和坐标，并从而获得驾驶过程中的速度图和加速度图。每一个参与者在长沙市区驾驶约30分钟。通过实地驾驶调查得到以下结论：

- 实际驾驶行为与调查问卷的结果相符合，问卷中的冒进指数在实际驾驶中得到了验证。冒进指数高的驾驶人在实际驾驶中也表现得更为冒进。
- 根据调查数据，不同驾驶人的速度特征与加速度特征均差异明显，并据此进行了驾驶风格分类。
- 驾驶行为的性别差异非常显著。驾驶行为与驾驶人的职业（专业司机或非专业司机），以及车辆类型（自动档或手动档）并不明显相关。
- 只要交通条件和驾驶任务变化不大，同一驾驶人在多次调查中的驾驶风格仍能保持稳定。
- 交通密度与驾驶人的加速度特性、减速度特性和车道变换行为负相关。

- 右侧超车和长时间占用最左侧车道均为常见驾驶行为。

焦点小组讨论

焦点小组讨论有助于了解参与者对某一问题的态度和观点。本研究组织了六次焦点小组讨论，以了解中国驾驶人对开车的态度，以及在不同交通条件下的特殊行为、驾驶偏好和习惯。

大多数参与者表示考驾照时所学交通规则在日常驾驶中被逐渐淡忘，而非加强。从而，不少驾驶人因不确定其他驾驶人的行为而不得不小心驾驶。这种驾驶观点非但不能有效解决实际交通中的冲突，反而会降低交通通行效率。大多数参与者还表示关于黄灯的交通规则表述模糊。他们并不清楚当自己的车是车队中的第一辆车，并在此刻遇到黄灯时，什么样的应对措施才是最恰当的。这些疑惑不但降低信号交叉口的通行能力，还增加交通事故的风险。

参与者证实交通状况（如：拥堵、长时间延误）能显著影响他们的驾驶行为。个人情绪，如着急、愤怒和不耐烦是驾驶行为的重要决定因素。

参与者描述了车道变换和超车行为中的一些特殊行为。首先，向左变换车道比向右变换车道需要较小的空档。礼让一般会提供给试图变换车道到右侧车道的车辆，而非给变至左侧车道的车辆。由于许多驾驶人喜欢长期占用左侧车道，从右侧超车就相应变得非常普遍。可接受的车道变换空档取决于交通条件，在交通密度大时往往通过强行变道实现。

焦点小组讨论显示改善中国城市中的驾驶行为可以从很多方面着手：加强交通的执法力度、驾驶培训和驾照考试中更侧重于安全行车意识、以及加强对所有道路交通参与者的交通规则教育。

基于驾驶行为调查的微观仿真模型参数标定

仿真模型需进行参数标定后才能模拟出较真实的交通特征，并应用于实际交通分析。多数情况下，模型的参数标定是根据实测的流量、行程时间和排队长度，而非详细的驾驶特征，如速度、加速度特点。然而，这些与驾驶特征有关的参数能在一定程序上决定仿真的细节，如：饱和流率和车辆排放。

本文利用在长沙进行实际驾驶调查时采集的GPS数据对微观仿真模型VISSIM进行

参数标定。根据真实驾驶数据绘制的速度和加速度曲线与模型采用默认值时所仿真的曲线完全不同。

敏感性分析确定出与速度和加速度仿真结果密切相关的驾驶行为参数。参数标定的目标是速度分布、加速度/减速度分布、饱和流率。行程时间是由期望速度、信号控制和饱和流率决定，所以不作为参数标定的目标。

实测的加速度不能直接用于期望加速度方程的确定。因为当车辆处于跟车状态时，驾驶人经常不能使用期望加速度。对期望速度的标定也有同样的问题。本文提出一种‘删失方法’，利用GPS数据对期望车速分布和加速度方程进行标定。跟车模型的参数是两两成对以饱和流率为目标同时进行标定。标定过程中的重复试验表明这一标定程序相当稳健。模型验证显示经标定后的模型能很好地模拟驾驶员在不同交通条件下行为。本文还对问卷调查和实际驾驶调查所确定的四种驾驶类型分别进行了参数标定。不同的驾驶类型在期望速度和最大期望加速度/减速度中存在显著差异。如将驾驶类型的区分应用于未来的参数标定，则标定工作能简化为确定不同类型驾驶人的比例。

利用GPS追踪车辆是一种方便的数据采集方式，并能揭示同一驾驶人在不同交通条件下的行为差异。本项研究也显示仿真程序在模拟某些驾驶特性时的局限性。比如，仿真程序不能模拟由于驾驶任务、个人情绪和交通条件而导致的驾驶行为差异。

对仿真模型改进的建议

交通仿真模型已广泛应用于交通规划、交通评估和交通设计中。大多数模型的建立是基于相对规范的驾驶行为。本研究表明模型的改进和相关参数的标定需符合真实的驾驶行为。

即便同一驾驶人的驾驶风格可以改变，仿真程序仍需区别不同的驾驶类型。保守和冒进驾驶人的分布应该取决于交通状况。本研究还表明由西方国家研发的仿真模型应该针对中国的驾驶行为进行修改，尤其应考虑饱和车流、车辆变换和让行方面的不同。同时还应考虑的是交通条件对驾驶行为产生的影响。目前的模型并不存在交通条件影响驾驶行为的关系式。因此有必要定义一个外挂函数，将交通条件与普通的驾驶行为模型相联系。

About the Author: Curriculum Vitae and List of Publications

Jie Li was born in You County, Hunan Province, China, in 1972. After graduating from Hunan City University in 1992, she worked as an engineer of road engineer at a company for several years. From 1999, Jie Li studied as a master student at Hunan University. In 2002, she received her MSc degree of highway & railway engineering. Afterwards, she became a teacher at the College of Civil Engineering, Hunan University. She gives several courses: Road Survey and Design, Road Intersection Design, etc., and does research on transportation and road engineering.

In 2007, Jie Li started her PhD research at Delft University of Technology when she received a ten-month scholarship from NUFFIC. Thereafter, Jie Li continued her research with the finance from CSC, DVS, etc. During the period of 2007-2014, she did the comparative study on driver behavior between China and the Netherlands, published several journal papers, and presented papers at various conferences. Being a married lady and a mother, Jie Li conducted her PhD study part-time, meanwhile working as a teacher at Hunan University in China.

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