NECESSITY ANALYSIS OF INSIDE SHOULDER FOR MULTI-LANE FREEWAY

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ABSTRACT:
By the end of 2014, the total mileages of freeway in China have reached 112,000 kilometers, ranking the first in the world. Most of freeways are four-lane or six-lane, for which inside shoulder is not required by current Chinese guidelines. The inside shoulder is designed to reduce the possibility of fatal traffic accidents on freeways. In China, “Technical Standard of Highway Engineering” regulates that 2.5-meter width inside shoulder should be provided in eight-lane freeways. Several old four-lane or six-lane freeways have just been reconstructed into eight-lane roadways without adding inside shoulder, and even without side strips wider than 0.75 meter. Meanwhile, few studies have systematically analyzed the advantages of inside shoulder for multi-lane freeway. Based on the statistical analysis of accident data, the theoretical modeling and simulation of lane-changing theory, as well as the cost-benefit analysis, this paper studied the effects of inside shoulder on the operational efficiency and traffic safety, and further demonstrated the necessity and feasibility of inside shoulder for the multi-lane freeways.

KEY WORDS:
Inside shoulder, Traffic safety, Gap acceptance theory, Traffic simulation, Cost-benefit Analysis
1. INTRODUCTION

Most of the freeways in China are two-way four-lane or six-lane, in which the inside shoulder was not required except the subgrade separated freeway. With the increase in the number of freeway lanes, providing the inside shoulder is inevitable. The inside shoulder has different role compared to the right shoulder, among them the most important role is to provide the side clearance and fault-tolerant space for the high-speed vehicles in inner lane, as well as provide temporary parking place in cases of emergency, so the vehicles need not cross multiple lanes to park on the right shoulder. The existence of inside shoulder is not only good for the improvement of the overall traffic operating efficiency, but also help to avoid severe traffic accidents (ZHONG, 2011, Hadi, 1995, Stamatiadis, 2009, Horst, 2007).

Although several researchers and officials have considered the issue of inside shoulder and “Technical Standard of Highway Engineering” also has the regulation that eight-lane freeway should contain 2.5-meter width inside shoulder (MOT, 2014), several construction of freeways just focused on eight-lane widening, such as Shanghai-Nanjing Freeway, and Shenyang-Dalian Freeway, and Guangzhou-Foshan Freeway, without installing inside hard shoulder, nor even wider than 0.75-meter curbs.

The regulation or installation criteria about hard shoulder can be found in the road design standards and specifications of other countries. Compared with those of United States and Japan, the value of right shoulder width of China is in between. In general the shoulder width is 2.5 meters with the 1.75-meter minimum for freeway in Japan. In American specifications the shoulder width are determined by many factors. Shoulders should be installed in both sides, and the right shoulder is at least 10 feet, and when truck volumes are higher than 250 per hour, the right shoulder is best to reach 12 feet. For the four-lane freeway, usually the inside hard shoulder width is between 4 feet and 8 feet. The width of inside shoulder for six or more lanes freeways should be at least 10 feet. When truck volumes are higher than 250 per hour, the shoulder width should be 12 feet (AASHTO, 2001). The inside shoulder of the highway specification in China for renovation and expansion into the eight-lane freeway and newly built eight-lane freeway is non-mandatory provision, and the standards are mainly referred from some foreign practices (AASHTO, 2001, Leisch, 2006, Pline, 1999). The main reason is that there are no relevant researches to provide theoretical support and also no knowledge on the functions of inside shoulder. At present more considerations to be made about the freeway design issues such as land conservation and cost reduction during freeway renovation and expansion, which may lead to a huge negative impact on the operation of the freeway in future.

![Figure 1: Freeway cross section comparison between the USA and China](image)

There was no thorough research about freeway inside shoulder in China and the majority of the studies focused on the horizontal alignment and vertical alignment design of highway. In this study, the necessity of inside shoulder is investigated based on the statistical analysis of accident data, the modeling and simulation of lane-changing theory, as well as the cost-benefit analysis. The findings
proved the significance and necessity of the inside shoulder of multi-lane freeway from the aspects of both safety and efficiency.

2. STATISTICAL ANALYSIS BASED ON FIELD ACCIDENT DATA

Three freeways which just completed reconstruction into eight-lane were investigated. The traffic accident data include lane position were used for further analysis. In the analysis process, the lane from left to right are named as "4", "3", "2", "1" in one direction and "5", "6", "7", "8" in another direction. Therefore, the “1” and “5” are the lanes which on the most left side (the inner lane). These three freeways have no inside shoulder, while the width of the side strip on the left is 0.75 meter. Figure 2 is accidents’ distribution by lanes in one of the three freeways.

![Figure 2: Accident distribution by lanes of one freeway.](image)

According to the statistical analysis of traffic accidents on eight-lane freeways, it can be concluded that most accidents occur in the side lane (including the inner and external lanes) in China, which accounting for about 65% of all accidents. Accident frequency of the middle two lanes are relatively low, and the ratio of accidents occur on left and on right is 32:68. This is mainly due to the high driving speed and frequently overtaking on inside lane, while there is no fault tolerance space for driving cars. Because of the frequently merging and diverging of traffic flow in outer lanes, conflict between vehicles leads to more accidents. The main two types of accidents occur in the side lanes are bumping guardrail and overturned. The accident ratio of Bumping guardrail is about 60%-70%, while the accident ratio of overturned is about 20%.

The analysis showed that the majority of accidents are directly or indirectly related to the inside shoulder provision. And it is clear that the safety situation will be greatly improved if the inside shoulder is provided in eight-lane freeways.

3. THE PROBABILITY AND DISTANCE MODEL OF VEHICLE DRIVES FROM THE INNER LANE TO RIGHT SHOULDER

This study assumes vehicles in the inner lanes have to drive across multiple lanes to reach the right shoulder when there is no inside shoulder for stop in cases of emergency. This process not only impact the operational efficiency of straight traffic, but also has great potential safety hazard. A probability
and distance model in this case is established, which is based on gap acceptance theory regarding different volumes and lanes.

3.1. The probability of a vehicle moves from the inside lane to the right shoulder

For convenience, it is assumed that the distribution of headway of different lane all follow the negative exponential distribution at any time (or position). So the distribution function is as follows:

\[ F(t) = 1 - e^{-\lambda t} \] (1)

Where: \( \lambda \) : average vehicle arrival rate, \( \lambda = \frac{Q}{3600} \), \( Q \): traffic volume per hour of each lane.

The vehicle of the left lane can cross to the right lane only when the headway of right-side vehicles \( H \geq \alpha \) (\( \alpha \) is critical gap). So the acceptance probability of any gap of the adjacent right lane can be expressed as:

\[ P(H \geq \alpha) = e^{-\lambda \alpha} \] (2)

So only when the headway of all right lanes meets \( H \geq \alpha \), the vehicle in the left lane can succeed in crossing all the straight lanes successfully and stop on the right shoulder. According to the formula of probability theory: \( P(A \cap B) = P(A) \cdot P(B) \), it can be drawn that the successful probability is \( e^{-3\lambda \alpha} \) and \( e^{-4\lambda \alpha} \) respectively when a vehicle transfers from the inner lane to the right shoulder of 8-lane and 10-lane freeway. Further the probability not successful (rejected) of 8-lane and 10-lane freeway is \( 1 - e^{-3\lambda \alpha} \) and \( 1 - e^{-4\lambda \alpha} \) respectively.

Based on the some researches, \( \alpha \) was taken as 2.6s, 2.8s and 3.0s and the rejection probabilities under different traffic conditions were calculated as shown as follows.

\[ \begin{align*}
0 & \quad 500 & \quad 1000 & \quad 1500 & \quad 2000 & \quad 2500 \\
\text{Reject Probability} & \quad \text{volume (veh/h/lane)} \\
5 \text{ lanes} & \quad 0 & \quad 0.1 & \quad 0.2 & \quad 0.3 & \quad 0.4 & \quad 0.5 \\
4 \text{ lanes} & \quad 0.6 & \quad 0.7 & \quad 0.8 & \quad 0.9 & \quad 1 \\
\text{3 curves in both 2 groups: critical gap of upper, middle and lower is 3s, 2.8s, 2.6s respectively} \\
\end{align*} \]

Figure 3: Rejection probability distribution of volumes, lanes and critical gaps

From Figure 3, it can be observed that with the increase of the flow rate, the accepted gap which is provided by headways is getting smaller and smaller, namely it is more difficult for vehicles to catch
the gap when the traffic volume reaches larger. And the more lanes, the greater rejection probability, similarly the bigger critical gap, the greater reject probability. Relatively the impact of volume is bigger than that of lanes.

3.2. Distance analysis as vehicle transfer from inside lane to right shoulder

Based on the reference (ZHONG, 2011), the distance of vehicle changing one lane can be divided into three parts: (1) the travel distance when vehicle waiting for the acceptance gap in the left lane, (2) the travel distance that the acceptance gap is judged and confirmed, (3) the travel distance of lane shifting of the vehicle. So the distance that the vehicle shift a lane can be calculated as follows:

\[ L = \frac{V}{3.6} \cdot \frac{1}{\lambda} (e^{\lambda \alpha} - \lambda \alpha - 1) + \frac{V}{0.9} + \frac{V}{1.2} \]  

Where: \( V \) : the operation speed.

According to the HCM 2010 (TRB, 2010), the operation of freeway can not maintain at both high speed and volume, so this paper conducts the following analysis and hypothesis: At the speed of 120 km/h, the maximum flow can not exceed 1300 veh/h/lane; at the speed of 100 km/h, the maximum flow rate is 1600 veh/h/lane; and at speed of 60 km/h and 80 km/h, the maximum flow can reach 2200 veh/h/lane. Thus \( \alpha \) is taken as 2.6s according to the formula (3) the figure 4 is obtained.

![Figure 4: Distance of one lane change in different speeds and volumes](image)

It can be observed that with the increase of speed and volume, the distance of lane changing will increase. And the relationship between speed and distance is proportional. The figure 4 represents the distance of one lane changing, so for a one-way 5-lane freeway, the distance of transfer should be 4 times of the figures’ value. It will take longer distance for the vehicle to change more lanes. It requires about 900 meters to cross to the right shoulder from inner lane on a one-way 5-lane freeway when the volume is 1000 per hour.
The above modeling and analysis is in a very ideal condition, and some parameters such as vehicle type are assumed simply. In real situation, there are lots of trucks and the critical gap is usually larger, as a result the distance of transfer should be larger at the same conditions. The frequent lane changing is easy to cause heavy pressure to the driver’s psychology which lead to improper operation, so the possibility of accident is aggravated.

4. IMPACTS OF CROSS BEHAVIOR ANALYSIS
The previous analyzed the distance of the vehicle transfers from the inside lane to right shoulder at a certain speed. While in the real situation, the vehicle may not keep the same high speed especially with some power failures. So the mandatory lane changing may happen, and this manner has great impact on the straight traffic under big volume and more lanes.

4.1. Trial Objective and Project Design
To demonstrate the behavior that a vehicle moves from the inside lane to the right shoulder through the straight traffic, the road environment which is shown in Figure 5 was built in VISSIM. The configuration is a 4-lane weaving section which could be equal to the 10-lane freeway without inside shoulder in reality. This process is the same as that a vehicle moves from the inner lane to the right shoulder in 10-lane freeway. The purpose that fixing the lane-change distances in the simulation analysis is to analyze the impact of different distances on speed.

Simulation inputs primarily consist of three aspects: (1) Lane numbers in weaving section: 3 lanes and 4 lanes represent 8-lane and 10-lane freeway without inside shoulder. (2) Input flow: 4 types: 500, 1000, 1500, 2000 vehicles per hour per lane. For better comparison all vehicles are assumed as passenger cars in the system. (3) Lane-change distances (the length of weaving section): from 100 meters to 1000 meters with 100-meter interval, so a total of 10 cases. To summarize, there are total of 2x4x10=80 different cases in the simulation.

Ideal simulation condition is that the process only one vehicle enters to the basic section then change lanes and exit from the right ramp was studied, which is a little difficult considering the sample and the randomness of simulation. So a substitute process that the vehicles enter the weaving section at a 10-second interval in 1 simulation hour was studied. The virtual detectors were placed in the middle of and 50-meter down the weaving section for record the operation speeds.

4.2. Analysis and Discussion
Figure 6 is a screenshot of the process of traffic simulation. It shows that short distance of weaving caused lots of straight vehicles queuing and stops, and the more lanes, the more evident of this
phenomenon. Frequent brakes, and lane changes make an increase in conflicts, which prone to accidents like rear-end and side-wipe crashes according to Traffic Conflict Theory, so the mandatory lane changing is potential dangerous significantly, meanwhile affects the capacity and level of service of the freeway (TRB, 2010).

Figure 6: Virtual operation in simulation

Figure 7 provides a more explicit explanation of the result that the speeds of different lane-change distances of 4-lane freeway when the volume input is 1000 veh/h/lane. The speed in the weaving section and at downstream area are both subject to the lane-change distances, especially that in the weaving. The average operation speed is only 9.4 km/h in the weaving section when the distance is 100 meters, and 11.7 km/h for the 200-meter distance. With the increase of the lane-change distance, the speed in weaving section also gradually increase, and when the distance is more than 500 meters, the speed in the weaving section maintains at the range between 70 km/h and 80km/h. Relatively the speed downstream is less affected by the lane-change distance. With the distance increasing, there is also a growing trend of the speed. The minimum of speed downstream is 63 km/h, appears in the lane-change distance of 200 meters, and the maximum is 97 km/h under the maximum lane-change distance, namely, 1000 meters.

Figure 7: Speed comparison of different lane-change distances under the condition of 4-lane and 1000 pcu/h/lane

The influences of volume input and number of lanes can be seen in Figure 8.
The results of analysis indicate that when the volume input is less than 500 veh/h/lane the speeds in the weaving section and downstream are almost the same and affected weakly by lane numbers. When the volume of each lane is 1000 veh/h, the speed difference between in the weaving section and downstream is not particularly large, and the speed downstream is about 20 km/h higher than that in the weaving section. As the flow increased to 1500 veh/h/lane, and to the 2000 veh/h/lane, the speed in weaving section decreased sharply and the value is only 20 km/h around. While the speed downstream reduces step by step and when the flow rate is 2000 veh/h lane, the speed downstream is 64 km/h for 4-lane and 65 km/h for 3-lane weaving section. It also can be seen from Figure 8 due to one less lane-changing behavior the speed downstream of 3-lane weaving section is bigger than that of 4-lane weaving section. The maximum speed difference appears in the volume input of 1500 veh/h/lane, and the speed downstream is 86 km/h for 3-lane weaving section as well as 67 km/h for 4-lane weaving section.

5. COST-BENEFIT ANALYSIS

This paper applies the "with and without comparison" method on cost-benefit analysis of inside shoulder. By analyzing the investments of reconstruction to eight-lane freeway in domestic, the price of setting inside shoulder can be determined. Through analyzing the accidents data, the economic loss of accidents related to the left space of inner lane such as crash median guardrail etc. are ensured. Then, the investment costs and benefits of inside shoulder are compared.

5.1. Cost estimation of inside shoulder addition

Investment budget of freeway expansion involves terrain, project removal, as well as the consideration of new construction and renovation of the bridge and service facilities etc. so it is difficult to accurately calculated invest funds per kilometer. In order to estimate cost of investment for the addition of inside shoulder, the costs of renovation and expansion of several typical freeways in 2003-2012 were analyzed. The average investment cost of 7 4-lane expanded to 8-lane expressways is 54.32 million RMB per kilometer. Traffic engineering, environmental protection and greening, as well as overpass and underpass removal etc. would not basically increase the cost whether there is inside shoulder or not. And this cost proportion is 24.67% of the total investment. According to the shoulder width regulation of "technical standard of Highway Engineering", Addition of inside shoulder to 8-lane freeway is equivalent to an increase of a lane, as a result the cost increased one fourth. The long-
range year of traffic volume prediction when freeway construction in China is usually the 20th year in future. So calculated by the use of 20 years, the expense of average annual investment increased is 511.5 thousand RMB per kilometer per year.

5.2. Benefit estimation of inside shoulder addition
The benefit of inside shoulder mainly reflected in less of accidents, and it will play the safety role in every year with repeatability. In the previous part of “accident analysis”, it can be concluded that the central median roadside accidents accounted for about 16% of all accidents. Many researches believe that most traffic accidents can be avoided with inside shoulder set, and severity will be reduced partly. Precise benefit estimation in this paper is very difficult, and in order to do such a job some useful data were collected for calculation. The crash rate of typical 4-lane freeway of eastern plain terrain is 6.64 per kilometer per year in China. The cost of accident included the number of casualties, the damage of vehicle and road, the loss of social organization and traffic delay etc. According to the relevant research results in "Road Safety Manual of China" (TANG, 2009), the average cost of each accident is 272 thousand RMB in 2006 in China. Since the traffic volume has an absolute positive effect on the accident number, so the benefit of 8-lane freeway is twice that of the 4-lane freeway was assumed reasonable, therefore the benefit of inside shoulder addition is 598.6 RMB per kilometer per year. So it can be concluded that the benefits are greater than the costs when 4-lane expanded to 8-lane with inside shoulder. As we all know the service life of freeway is more than 20 years, and the actual situation is indeed the case. So the benefits are more. The above cost benefit analysis proved that it is worthy to set inside shoulder on the 8-lane or 10-lane freeway in China at present. On the other hand, it has to say the calculations of accident loss as well as increase of investment budget of inside shoulder addition are very difficult to accurately estimate, so this paper adopted some average value based on typical freeways from some references and reports. Anyhow, the results have some value for reference.

6. CONCLUSION
Firstly, this paper facilitated a statistical analysis based on field accident data. The result showed that the inner lane and external lane accounted for a larger percentage of accident on eight-lane freeways. And the provision of inside shoulder will make a positive effect to reduce crashes.

Secondly, with assumption that vehicles in the inner lanes would have to drive across multiple lanes to reach the right shoulder given no inside shoulder to be used in cases of emergency, a probability and distance model was established, supported by gap acceptance theory regarding different volumes and lanes. It was more difficult for vehicles to catch the gap when the traffic volume increased. And it would take longer distance for the vehicle to change more lanes. Most import issue was that safety risks were very prominent during this process.

Then, the impacts were analyzed for the behavior that a vehicle moved from the inside lane to the right shoulder across the through traffic of one 8-lane and another 10-lane freeway. By using simulation method, the operation speeds in weaving section and downstream were exploited under different volumes and lane-changing distances. The vehicle speeds in weaving section and downstream were compared under the same volume input and different lane-changing distances, as well as under the same lane-change distances and different volume inputs and number of lanes. The analysis showed that it was likely to cause queuing on main roadways when the flow was larger, and also led to more conflicts in downstream. This may result in a lot of potential safety concerns.
Finally, this study applied the "with and without comparison" method on cost-benefit analysis of inside shoulder. Though adding inside shoulder would increase the cost of construction, it will decrease cost of traffic accidents in a long term. Considering the overall social and economic benefits, the inside shoulder is worthy to be installed.

All the results indicated the significance and necessity of the inside shoulder of multi-lane freeway in China. Furthermore this research provided ideas and methods for the freeway cross-sectional and alignment optimization design, and also built a theoretical basis for the revision and improvement of freeway design standards and specifications.

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