Safety and Capacity Performances of Single-lane Right Exit Ramp on Freeway: A Case Study in Jiangsu Province, China

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Abstract

Growing traffic in China has resulted in a demand for freeway exit ramps with higher capacity in order to avoid congestion. The right single-lane exit ramp is the most common style of the freeway exit ramp which can be divided into two types: taper-type single-lane exit ramp and parallel-type single-lane exit ramp. The main objective of the paper was to elaborate recommendations about the best single-lane exit ramp layout according to different parameters by evaluating safety and capacity. 6 taper-type and 4 parallel-type exit ramps were selected in Jiangsu Province and the space mean speeds (SMS) of the 200 vehicles on the deceleration lane of each sample were observed. The average SMS standard deviation of taper-type was 8.0 kmph comparing with 4.6 kmph of parallel-type, which indirectly indicated that parallel-type single-lane exit ramp was safer than the other one. The capacities of the two exit ramp types were analyzed using the FHWA’s Traffic Software Integrated System (TSIS). Two microsimulation models were constructed and the vehicle input varied from 0 to system alert “backed up” by each increment of 100 pcph. The capacity was defined as the input value before the system “backed up”. The results of the two exit ramp types were 1800 pcph and 2100 pcph, which meant the capacity of parallel type was more than the taper type.

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1. Introduction

As the rapid economic development in China, the construction of freeway speeds up. The freeway mileage in China reached 111,900 kilometers at the end of 2014 [1]. Freeways provide the highest level of mobility compared...
with other road types. Hence, a collision on a freeway is more likely to cause a fatality or a serious injury. Safety performance of freeway segments is affected by several factors including the entering and exiting movements at ramp terminals and associated maneuvers at the merge and diverge areas. Road users in such area are required to select and adjust speeds without causing undue dangers to themselves or to other road users. Such dangers would normally increase in terms of frequency and intensity with increasing volumes of vehicles entering and exiting a specific segment on the freeway.

The current guidelines are based mainly on implicit safety performance at the entrance and exit areas without a direct evaluation methodology. The most widely used methodology for analyzing merge and diverge areas is provided by the Highway Capacity Manual (HCM) [2]. This manual states that the operational effects due to merge and diverge maneuvers are most in the first two lanes adjacent to the speed change lane, as well as the speed change lane itself. This effect area extends for 450 m (1500 ft) downstream from the physical gore in the merge areas and 450 m (1500 ft) upstream from the physical gore of the diverge areas. According to the design guideline by the the Transportation Association of Canada, there is no evidence so far that merge and diverge maneuvers affect the capacity of the freeway mainline. The only effect is adding demand to or subtracting demand from the freeway [3]. However, developing the the crash prediction models between historic traffic crashe data and geometric elements at merge and diverge areas has been an active research field. Bauer and Harwood [4] studied the relationship between traffic crashes and highway geometric design elements and traffic volumes for interchange ramps and speed change lanes. Poisson and negative binomial regression were used to build the models for predicting crashes on ramp sections and speed change lanes. Bared et al. [5] developed a model to estimate the crash frequency for entire ramps as a function of ramp annual average daily traffic (AADT), mainline freeway AADT, deceleration lane length and ramp configurations. Chen and Liu collected crash data at 343 freeway segments in the state of Florida and the crash prediction models were developed to identify the factors that contribute to the crashes of different types of freeway exit ramps. It was found that the ramp and freeway AADT, posted speed limit on freeway, deceleration lane length, right shoulder width, and the type of exit ramp significantly affected the safety performance of freeway diverge areas [6-8].

The need for need for undering capacity is critical, as reflected in the HCM. The HCM procedures are the most widely used in the world, however, they estimate level of service (LOS) but not capacity. The UK Standard provide engineers a diverging flow-region diagram to help on the selection of the most appropriated layout depending on the mainline and diverging flows [9]. Five layouts were considered: taper, parallel, taper lane drop, parallel lane drop, and parallel double lane drop. The regions were formed based on the maximum design working flows on both diverging and mainline. Both taper diverge and lane drop at taper diverge had a capacity of 1400 vph, while parallel diverge had 1800 vph capacity. Two-lane exit ramps presented capacity of 3600 vph at lane drop and lane drop at parallel diverge [10]. Nevertheless, the supports of these figures are unclear [11].

Freeway exit ramps are the sites with many driving behaviors and conflicts, which could result in higher traffic crashes compared with other freeway segments or sites. Inadequate design could result in reduced capacity on exit ramps, which could result in traffic “spill out” to main freeway lanes and significant reduction in main segment capacity. Besides, inadequate design may cause high crash frequency in the impact areas of exit ramps. Compared with freeway entrance, exit ramp is more dangerous through a study by Lundy who reported that exits were associated with higher collision rates than entrances [12]. And then, the more statistical data have shown that freeway exit ramps could result in about double number crashes compared to freeway entrance ramps [13].

The single-lane right exit ramp is the most widely used layout on freeways in China, which can be divided into two types: taper and parallel, according to the Chinese Standard [14]. They are shown in Fig. 1. The standard recommends to select taper type for single-lane exit ramp in application, however, no reason is given. Ma et al. [15] compared the maximal operational volumes of four types of freeway exits ramps including single-lane right exit by simulation, nevertheless, the safety performances were not considered.

The aim of the present paper was to elaborate recommendations about the best freeway single-lane right exit ramp layout by evaluating their safety and capacity performances in the meantime.
Speed standard deviation (SSD) was used as a surrogate measure for evaluating the safety performance since the detailed accident records are hardly collected through a regular way. The distinct relationship between crash rate and speed dispersion has been proven by many previous researches [16,17]. The space mean speeds (SMS) of diverging vehicles on taper and deceleration lane of the taper and parallel exit ramp layouts were collected and the results revealed the safety performances.

Traffic simulation was used to estimate capacity on diverge areas since the complexity of the capacity in diverging area. Two traffic simulation models were created for the purpose of this research. To make the models similar to the ones in real world; a calibration procedure was provided.

The research of this paper included two main components: safety performance and capacity performance. Each content is being developed as the following sections.

2. Safety Performances

The standard deviations of space mean speeds were applied to illustrate the safety performances of two types of single-lane right exit ramp.

2.1. Field Data Collection

A field study was carried out to obtain actual vehicle speeds on taper and deceleration lane of single-lane right exit ramp. 6 taper samples and 4 parallel (parallel type exit ramps are rarely applied in China) samples were selected along Huning Freeway and Ninggao Freeway in Jiangsu Province of China, and they are listed in Table 1. The speed limit of the mainline for all the samples is 120 kmph, and the ramp speed limit is 40 kmph.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Site</th>
<th>Direction</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Huning-Changshen Interchange</td>
<td>Nanjing to Shanghai</td>
<td>Taper</td>
</tr>
<tr>
<td>2</td>
<td>Huning-Changshen Interchange</td>
<td>Shanghai to Nanjing</td>
<td>Taper</td>
</tr>
<tr>
<td>3</td>
<td>Huning-S243 Interchange</td>
<td>Nanjing to Shanghai</td>
<td>Taper</td>
</tr>
<tr>
<td>4</td>
<td>Huning-S243 Interchange</td>
<td>Shanghai to Nanjing</td>
<td>Taper</td>
</tr>
<tr>
<td>5</td>
<td>Huning-Yangli Interchange</td>
<td>Nanjing to Shanghai</td>
<td>Taper</td>
</tr>
<tr>
<td>6</td>
<td>Huning-Yangli Interchange</td>
<td>Shanghai to Nanjing</td>
<td>Taper</td>
</tr>
<tr>
<td>7</td>
<td>Huning-Hui Interchange</td>
<td>Nanjing to Shanghai</td>
<td>Parallel</td>
</tr>
<tr>
<td>8</td>
<td>Huning-Suzhou Industrial Park Interchange</td>
<td>Nanjing to Shanghai</td>
<td>Parallel</td>
</tr>
<tr>
<td>9</td>
<td>Ninggao-Shatang Interchange</td>
<td>Gaochun to Nanjing</td>
<td>Parallel</td>
</tr>
<tr>
<td>10</td>
<td>Ninggao-Ninghang Interchange</td>
<td>Gaochun to Nanjing</td>
<td>Parallel</td>
</tr>
</tbody>
</table>

The time that the vehicle passing the beginning point of the taper and the nose on the ramp were recorded continuously by two surveyors. The locations are illustrated in Fig. 2. The surveyor 1 at the beginning of the observed the approaching vehicles, if one vehicle made a lane change from inner lanes to outer lane or the right-turn indicator flashed, the surveyor 1 recorded the time when the vehicle passed the beginning point of the taper, meanwhile, he signaled the surveyor 2 to record the time when the vehicle passed the nose. The length of the taper...
and the deceleration lane of the sample exit ramp was calibrated by Google Earth, and the SMS of that vehicle was obtained. The formula to calculate the SMS is shown in Equation (1).

\[
SMS = \frac{T_{\text{nose}} - T_{\text{taper}}}{L_{\text{taper}} + L_{\text{deceleration}}}
\]  

(1)

where SMS is the space mean speed of the vehicle on the taper and deceleration lane; \(T_{\text{nose}}\) is the time the vehicle passing the nose of the exit ramp; \(T_{\text{taper}}\) is the time the vehicle passing the beginning point of the taper; \(L_{\text{taper}}\) and \(L_{\text{deceleration}}\) are the the lengths of taper and deceleration lane, separately.

![Diagram](image)

Fig. 2. Locations of time recording by two surveyors: (a) taper; (b) parallel.

2.2. Data Analysis

The samples listed in Table 1 were selected and 200 vehicles of each sample were observed. The SMS of each vehicle was calculated by Equation (1), and the SSD of each sample was calculated as Equation (2).

\[
SSD = \sqrt{\frac{\sum_{i=1}^{n} SMS_i^2 - (\sum_{i=1}^{n} SMS_i)^2}{n(n-1)}}
\]

(2)

where SSD is the speed standard deviation; SMS\(_i\) is the space mean speed of the vehicle \(i\) on the taper and deceleration lane; \(n\) is the number of the observed vehicles of one sample, \(n=1,2,\ldots,200\). The results are listed in Table 2 and Table 3, and the comparisons between the taper type and parallel type are illustrated in Fig. 3.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Average SMS (kmph)</th>
<th>Average SSD of SMS (kmph)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>83.3</td>
<td>8.35</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>78.8</td>
<td>7.69</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>76.5</td>
<td>7.58</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>62.1</td>
<td>8.03</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>66.4</td>
<td>8.77</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>70.9</td>
<td>7.41</td>
<td></td>
</tr>
</tbody>
</table>

The average standard deviation of the space mean speed of taper-type exit ramp samples is 8.0 kmph, which is more than the 4.6 kmph of parallel-type samples. The results indicates that the vehicle speed disperses more widely around the taper-type diverging area, that means the safety performance of the parallel-type single-lane right exit ramp is better than the one of the taper-type exit ramp in operation.
3. Capacity Performances

Traffic simulation was used to estimate capacity on single-lane right exit ramps since too high volumes in suburb areas and too low volumes in rural areas, and the traffic flows close to capacity are hardly observed in China. Two traffic simulation models were created for the purpose of this research by FHWA’s Traffic Software Integrated System (TSIS 5.1). To make the simulation models as similar as possible to the ones in real world, the strict calibrating procedure was carried out as follows.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Average SMS (kmph)</th>
<th>Average SSD of SMS (kmph)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>72.1</td>
<td>6.34</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>62.7</td>
<td>4.26</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>65.5</td>
<td>3.33</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>63.4</td>
<td>4.55</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Comparisons of SMS and SSD between taper and parallel single-lane right exit ramps.

3.1. TSIS Calibration

Avoid hyphenation at the end of a line. Symbols denoting vectors and matrices should be indicated in bold type. Scalar variable names should normally be expressed using italics. Weights and measures should be expressed in SI units. All non-standard abbreviations or symbols must be defined when first mentioned, or a glossary provided.

TSIS can simulate all kind of exit ramp configurations so that the impacts of exit ramp types on traffic operations can be analyzed (SEH 2008, Nevada DOT 2012). Based on a field survey, the parameters of TSIS-package were calibrated in order to be applied in the research. Traffic data, including flow data and geometric data, were collected to calibrate TSIS models. To calibrate the parameters of the simulation models, a prototype of North Yangzhou Exit of Yangli Freeway (eastward) was set up and the traffic data were collected. The calibration steps are given as follows:

- Step 1: Measure the average vehicle speeds and volumes in the mainline and ramp of the North Yangzhou Exit.
- Step 2: Input the initial values of the parameters and the field traffic data collected to the TSIS prototype.
- Step 3: Collect the simulated output of vehicle speeds and volumes in the mainline and ramp.
- Step 4: Calculate residual errors of vehicle speeds and volumes using Equation (3).
\[ RES = |SIM - DET| \]

where \( SIM \) is the simulated average volume (pcph) or average vehicle speed (mph); \( DET \) is the measured average volume (pcph) or average vehicle speed (mph).

Step 5: If both of the residual errors of volumes in the mainline and ramp are within 10% of the measured data; and both of the residual errors of vehicle speeds in the mainline and ramp are within 20% of the measured data, the statistics are acceptable and the model is calibrated. If they are not, then modify the parameters until the statistics are acceptable (SHE, 2008).

The 30 continuous simulation runs were carried out to reduce the random errors. All of the residual errors are less than 10% of the measured average volumes and speed on mainline or ramp (see Fig. 4), which proves the validity of the TSIS models.

![Fig. 4. Residual Error Ratios (Residual Error/Measured Date) of Average Volume and Speed.](image)

### 3.2. Simulation Outputs

Two types of the single-lane right exit ramp were simulated under the following conditions: 2 mainline lanes for one direction; single-lane right exit ramp; 120 kmph free-flow speed on mainline, 40 kmph free-flow speed on ramp, 20% turning rate and 100% passenger car. The simulation analysis was conducted with volume range of 0 pcph to 5100 pcph increasing by the pace of 300 pcph. The main purpose for the simulation analysis is to determine the best exit ramp type under given conditions. 30 continuous runs under same given conditions were performed and the average values were used to represent the simulation results.

Fig. 5 presents the relationship between traffic volume and average speed under the simulation conditions. The upstream, downstream and ramp in Fig. 5 mean the areas 450 m upstream, 150 m downstream and 100 m the ramp itself from the physical gore (nose), separately. The parallel-type single-lane right exit ramp performs better operation effects on the change of volume and speed than taper-type exit ramp. When the volume raises, the speed change of parallel type is relatively insensitive than the taper type, that means the parallel-type exit ramp has a better trafficability than the other type.
To compare the capacities of the 2 types of exit ramps, the vehicle turning rate was raised up to 100% in the simulation models. With the volume input increasing by a pace of 100 pcph, the vehicle number running though the exit ramp increased. When the package presented “backed up”, the volume could be approximately considered as the capacity under the simulation conditions. Table 4 shows the results of the capacities of two exit ramp types.

Table 4. Capacity of two types of single-lane right exit ramp under simulation conditions

<table>
<thead>
<tr>
<th>Type</th>
<th>Simulation Capacity (pcph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape</td>
<td>1800</td>
</tr>
<tr>
<td>Parallel</td>
<td>2100</td>
</tr>
</tbody>
</table>

Although the simulation operates under many assumptions and maybe there are great differences between the outputs and the reality, it can be concluded from Table 3 that the parallel type has a higher capacity than taper type. This finding is helpful.

4. Conclusion and Discussion

The single-lane right exit ramp is most widely applied on Chinese freeways, which can be divided into two types: taper and parallel. To recommend the best layout, 6 taper-type and 4 parallel-type exit ramps were selected in Jiangsu Province and the SMS of the 200 vehicles on the deceleration lane of each sample were observed. The average SMS standard deviation of taper-type was 8.0 kmph comparing with 4.6 kmph of parallel-type, which indirectly indicated that parallel-type single-lane exit ramp was safer than the other one. The capacities of the two exit ramp types were analyzed using the TSIS 5.1. Two microsimulation models were constructed and the vehicle input varied from 0 to system alert “backed up” by each increment of 100 pcph. The capacity was defined as the input value before the system “backed up”. The results of the two exit ramp types were 1800 pcph and 2100 pcph, which meant the capacity of parallel-type single-lane exit ramp was more than the one of taper-type single-lane exit ramp.

Compared with the taper-type exit ramp, the parallel type is safer and of a higher capacity in our research, however, the Chinses standard recommends to select taper type for single-lane exit ramp and no reason for this advice is given. The human factors, for example, comfort on different layouts, are not considered in the research, they may be for further consideration.

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References


