Research on Driving Risk Model of Freeway Interchange Entrance Area for Accident Prevention

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Abstract

Based on analysis of traffic characteristics of freeway interchange entrance area, Collision Risk Index (CRI) is put forward to evaluate driving risk. Possibility of collision coefficient, speed difference between two colliding vehicles, colliding speed and acceleration of the following car on the target lane are all taken into consideration in the risk assessment model of CRI. Traffic collisions that may occur in the entrance area are divided into five kinds. The occurrence conditions and risk assessment models of 5 cases are studied correspondingly. Finally, against running speed of main line, distance headway, running speed of vehicle on entrance ramp (front vehicle), three-dimensional numerical simulation has been carried out and driving risk variation laws have been obtained.

Keywords: Driving Risk; CRI; Interchange Entrance Area; Acceleration Lane; Three-Dimensional Numerical Simulation;

0. Introduction

Because of different driving behavior of straight-through and converging traffic flows, traffic behavior at freeway interchange exit-entrance area is much more complex than that of ordinary road segment. Accelerating and decelerating during vehicles entering or leaving the area, lead to frequent traffic conflict and easily lead to accidents. Survey data show that accident number at one exit-entrance area (include the ramp) of Hu-Ning freeway accounts for 15\% of all, and accident rate is 4.5 times of ordinary segment. Accident number at one exit-entrance area of Shen-Da freeway accounts for 13\% of all, and accident rate is 5.5 times of ordinary segment. [1] The above data indicate that safe problem at exit-entrance area is quite serious. By analyzing of driving risk of

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Founding of the research is provided by Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University (No. K201204) ; Guangdong Highway Administration (粤公研 2012-21) and Guangdong Communication Department(科技-2013-02-068).
exit-entrance area, clarifying influence factors of driving risk, and proposing risk evaluation model, theoretical basis can be formed to serve safety optimization design of exit-entrance area. Thus safe operation of freeway can be effectively improved. Because of different driving behaviors, the risks form is also different. Only driving risk of entrance area is studied in the paper.

Currently, there are many evaluation methods, such as Time To Collision (TTC), relative rate of gap change, safety coefficient, safety deceleration, and so on.[6] Real-time operation safety can be well reflected by these risk factors. However, these factors mainly based on car-following condition which is oblivious of lane changing behavior, and focus on single vehicle. In addition, to do good job of safety optimization design and management at entrance area, not only driving risk of one car should be studied, but also that of vehicles in certain region.

The paper introduces Collision Risk Index (CRI) to evaluate driving risk of cars at the entrance area, in which possibility and severity are both considered. The index is based on collision situation of car from entrance ramp and the following car on the target lane. CRI represents driving risk by distinguishing possibility and calculating severity of collision.

1. Characteristic of driving behavior at entrance area

   Driving behavior of converging traffic at entrance area characterized by the followings:

   - Mainline first
     The vehicle on accelerate lane will insert mainline only when the driver believes the gap is enough. Otherwise, he will wait.

   - Frequent lane changing
     Cars on accelerate lane entrance ramp want to insert mainline by changing lane from accelerate lane to near-side lane; straight-through cars switch from near-side to fast lane for comfort. As advance access sign is set up to warn straight-through cars, the risk of the latter is much small than the former. The paper focuses on studying on the former risk.

   - Influence on converging from accelerate lane
     When the car driving on the accelerate lane, the driver will adjustment speed according to the gap of near-side lane and insert the mainline when the gap is enough. Thus, suitable accelerate lane can guarantee safe and comfortable converging.

2. Risk evaluation model

   CRI is mainly based on 3 judgments: (1) whether car on the acceleration lane (denoted as Car-m) insert into target lane (near-side lane); (2) if the CAR-M switch to the near-side lane, will it brake; (3) when reaction time of the following car on near-side lane (denoted as Car-n) equals to the standard reaction time and the former car (Car-m) takes maximum deceleration, will they collide. The standard reaction time has been demarcated as average reaction time, and it is stated in many countries’ standard or norm. For example, it is stated as 2seconds in Sweden.

   Accident severity described in CRI is in collision energy terms. 4 parameters are considered:

   - Collision possibility coefficient p is used to indicate whether the collision is occurred: when there is a collision, p value 1 (p=1); when there is no collision, p value 0 (p=0).

   - Speed difference between two colliding vehicles is used to express the severity of the first collision (collision energy).
Collision speed \( v \) of following car on the target lane (near-side lane) is also used to represent the severity of the first collision (collision energy).

Decelerate \( a \) taken by Car-\( m \) when it switches from accelerate lane to near-side lane.

Space headway \( h \) at the converging moment.

Based on the above, formula of CRI is as follows:

\[
CRI = p \cdot I_v \cdot I_{\Delta v} \cdot I_m \cdot I_h
\]

Which:

- \( CRI \) -- Collision Risk Index;
- \( p \) -- Collision possibility coefficient. When there is a collision, \( p=1 \); when there is no collision, \( p=0 \);
- \( I_v \) -- Speed index. \( I_v = \frac{v_n}{v_{\text{max}}}, \) \( v_n \): speed of Car-\( n \) at the moment of collision [m/s]; \( v_{\text{max}} \): the maximum speed allowed on the mainline [m/s];
- \( I_{\Delta v} \) -- speed difference index. \( I_{\Delta v} = \frac{\Delta v}{v_{\text{max}}}, \) \( \Delta v \): speed difference between Car-\( m \) and Car-\( n \) at the moment of collision [m/s];
- \( I_m \) -- Decelerate ratio of Car-\( m \) and the maximum decelerate. \( I_m = \frac{a_m}{a_{\text{max}}} \);
- \( I_h \) -- Space headway index. \( I_h = \frac{h_{\text{safe}}}{h}, \) \( h \): space headway at the converging moment, \( h_{\text{safe}} \): safe space headway;

3. Determination of the parameters

Assuming reaction time of following car to be standard reaction time and the front car taking maximum decelerate, whether there will be a collision can be inferred by judging these parameters above. If occurs the collision, speed \( v \) of the following car and speed difference \( \Delta v \) between two cars can be calculated by principle of dynamics, as shown in fig. 1.

![Fig. 1. Sketch Graph Of Collision](image-url)
Base on assumption above, possible situation that may occur can be classified into 5 kinds:

- Following car can stop safely without collision in standard reaction time: \( p=0 \);
- 2 cars collide in standard reaction time and front car didn’t stop completely: \( p=1 \);
- 2 cars collide in standard reaction time and front car stopped completely: \( p=1 \);
- 2 cars collide after standard reaction time and front car didn’t stop completely: \( p=1 \);
- 2 cars collide after standard reaction time and front car stopped completely: \( p=1 \).

### 3.1. Determination of \( p \)

At the moment of Car-m converging into mainline (denote as \( t=0 \); denote the speed of Car-m as \( v'_m \); denote the speed of Car-n as \( v'_n \)), danger was discovered and the maximum decelerate (denoted as \( a_{m,\text{max}} \)) was taken by Car-m to emergency shutdown and the same action was taken by the Car-n after reaction time \( T \). Assume the space headway between two cars is large enough for Car-n to stop before collision, then:

\[
 h + \frac{v'_m^2}{2a_{m,\text{max}}} \geq v'_n T + \frac{v'_n^2}{2a_{n,\text{max}}}
\]

If the maximum decelerate of two cars is the same, then the condition of no-collision is as follows:

\[
 h \geq v'_n T + \frac{v'_n^2 - v'_m^2}{2a_{\text{max}}}
\]

\( p \) is valued as:

\[
 p = \begin{cases} 
 0 & h \geq v'_n T + \frac{v'_n^2 - v'_m^2}{2a_{\text{max}}} \\
 1 & h < v'_n T + \frac{v'_n^2 - v'_m^2}{2a_{\text{max}}}
\end{cases}
\]

### 3.2. CRI calculating model under different collision cases

**Case I:** the collision happens in reaction time \( T \) and the Car-m didn’t stop completely. \( t \leq T \).

In time \( T \), 2 cars collide together before Car-n can reaction. That is to say:

\[
 v'_m t \geq v'_n t + \frac{1}{2} a_{\text{max}} t^2 + h, \quad v'_n = v'_m + a_{\text{max}} t \geq 0
\]

Thus the collision time \( t_{\text{collision}} \) is:

\[
 t_{\text{collision}} = -\frac{\sqrt{(v'_m - v'_n)^2 - 2a_{\text{max}} h} - (v'_m - v'_n)}{a_{\text{max}}}
\]

The stop time of Car-m \( t_{\text{stop}} \) is:

\[
 t_{\text{stop}} = \frac{v'_m}{a_{\text{max}}}
\]

That is, when expression below is satisfied the collision happens before Car-n stops completely:
Denote the speed of Car-m at the collision moment as \( v_m \), and that of Car-n as \( v_n \):

\[
\text{CRI} = \frac{v_n}{v_{\text{max}}} \frac{\Delta v}{v_{\text{max}}} \frac{a_n}{a_{\text{max}}} \frac{h_{\text{safe}} - h}{h_{\text{safe}}} = \frac{v_n}{v_{\text{max}}} \frac{(v_n - v_m)}{v_{\text{max}}} \frac{h_{\text{safe}} - h}{h_{\text{safe}}}
\]

(2)

In case 1, \( v_n = v'_n \), \( v_m = v'_m + a_{\text{max}} t_{\text{collision}} \)

Other 3 cases can be deduced similarly, the results has been gathered in the table 1.

Table 1. Calculation models of CRI for 4 cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Judgment conditions</th>
<th>Calculate model</th>
<th>Explanations</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>( t_{\text{collision}} &lt; T ) and ( t_{\text{collision}} &lt; t_{\text{stop}} )</td>
<td>( CRI = \frac{v_n}{v_{\text{max}}} \frac{\Delta v}{v_{\text{max}}} \frac{a_n}{a_{\text{max}}} \frac{h_{\text{safe}} - h}{h_{\text{safe}}} )</td>
<td>( t_{\text{collision}} = \frac{\sqrt{(v_n - v'<em>n)^2 - 2a</em>{\text{max}} h}}{a_{\text{max}}} \frac{v_n - v'<em>n}{a</em>{\text{max}}} ) ( v_n = v'<em>n ) ( v_m = v'<em>m + a</em>{\text{max}} t</em>{\text{collision}} )</td>
</tr>
<tr>
<td>II</td>
<td>( t_{\text{stop}} &lt; t_{\text{collision}} &lt; T )</td>
<td>( CRI = \frac{v_n}{v_{\text{max}}} \frac{v_{\text{max}}}{v_{\text{max}}} \frac{h_{\text{safe}} - h}{h_{\text{safe}}} )</td>
<td>( t_{\text{collision}} = \frac{h}{v_n^2} \frac{v_n^2}{2v_n} \frac{a_{\text{max}}}{a_{\text{max}}} ) ( v_n = v'_n )</td>
</tr>
<tr>
<td>III</td>
<td>( T &lt; t_{\text{collision}} &lt; t_{\text{stop}} )</td>
<td>( CRI = \frac{v_n}{v_{\text{max}}} \frac{v_{\text{max}}}{v_{\text{max}}} \frac{h_{\text{safe}} - h}{h_{\text{safe}}} )</td>
<td>( t_{\text{collision}} = \frac{h - 1/2 \cdot a_{\text{max}} \cdot T^2}{v_n^2 - a_{\text{max}} T - v_n^2} ) ( v_n = v'<em>n + a</em>{\text{max}} (t_{\text{collision}} - T) ) ( v_m = v'<em>m + a</em>{\text{max}} t_{\text{collision}} )</td>
</tr>
<tr>
<td>IV</td>
<td>( T &lt; t_{\text{stop}} &lt; t_{\text{collision}} ) or ( t_{\text{stop}} &lt; T &lt; t_{\text{collision}} )</td>
<td>( CRI = \frac{v_n}{v_{\text{max}}} \frac{v_{\text{max}}}{v_{\text{max}}} \frac{h_{\text{safe}} - h}{h_{\text{safe}}} )</td>
<td>( t_{\text{collision}} = \frac{a_{\text{max}} T - v_n^2 - 2a_{\text{max}} T^2 + 2a_{\text{max}} h - v_n^2}{a_{\text{max}}} ) ( v_n = v'<em>n + a</em>{\text{max}} (t_{\text{collision}} - T) )</td>
</tr>
</tbody>
</table>

Fig 2 shows 3-dimensional numerical simulations of CRI for 80km/h, 100km/h and 120km/h, which varies with space headway and speed difference.

![Fig. 2. Three-Dimensional Numerical Simulation of CRI for different running speed of mainline](image)
With these figures, the following conclusion can be concluded:

- The bigger the speed of the car driving on the mainline (Car-n), the bigger the CRI;
- CRI decreases with the space headway increasing. With the increasing of the front car (Car-m), the speed difference becomes decreasing and the same to the CRI. When the speed of Car-m is bigger than that of Car-n, CRI reduces to 0. At this situation, driving risk between Car-m and the car before Car-m increases;
- When space headway reaches a fairly big value, CRI turn out to be 0, which indicates controlling space headway at interchange entrance area benefits for road safety.

4. Conclusion

The driving characteristic at freeway interchange entrance can be concluded as: mainline first; Frequent lane changing; obvious influence on converging. Based on these characteristics, CRI is advanced to evaluate driving risk. The main parameters of the model include collision possibility coefficient $p$, Speed difference between two colliding vehicles $\Delta v$, Collision speed $v$ of following car on the target lane $v$ and decelerate $a$ taken by Car-m. Furthermore, produced condition and evaluation model have been studied according to 5 cases. The model can be used to estimate safe level of converging area instead of traffic incident rate.

Acknowledgements

Founding of the research is provided by Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University (No. K201204).

References

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