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Speed-consistency Based Safety Evaluation for Freeway Diverging Segments

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Abstract. Diverging segments are potential bottlenecks because of frequent lane change and deceleration maneuvers. Speed study has been proven to be an effective way to understand the safety performance of diverging segments. This paper addresses the safety level of diverging segments in terms of speed consistency. Speed data is extracted by Tracker based on aerial video imager collected at the diverging segment of MaQun interchange of G42 in Nanjing, China. The operating speed of vehicles is assumed to follow the Linear Regression Model with two explanatory variables—initial velocity and running distance, and the estimated operating speed is amended under actual traffic conditions. Furthermore, average speed, speed difference and the coefficient of variation are used as safety indicators to establish the speed evaluation criteria. Last but not the least, based on vague set of material-units, the safety level of diverging segments in terms of the velocity arrives at level III, which means that consideration must be given about the safety of diverging segments. The proposed methodology can be used to estimate the safety of diverging segments.

1 Introduction

Freeways play a vital role in serving mega-cities, which could significantly raise the speed for mid and long distance traffic. Nevertheless, the efficiency and safety of freeways has been dramatically constrained by bottlenecks. Diverging segments may easily become bottlenecks because of frequent lane change and deceleration maneuvers. Therefore, understanding the efficiency and safety of diverging segments are important and necessary.

Freeway diverging segments occur primarily at off-ramp junctions with the freeway mainline [1]. Normally, there are two movements in diverging segments, namely mainline-to-mainline and mainline-to-ramp, which can affect the operations of each other. Influence area of diverging segments is defined as the deceleration lane(s) and Lanes 1 and Lanes 2 of the freeway for a distance of 450m upstream of the diverge point [1]. Figure 1 illustrates the influence area of diverging segments.

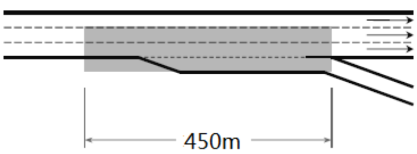


Figure 1. Influence area of diverging segment

Because of its importance and efficiency, diverging segments have already gained considerable attention from researchers. The capacity studies of diverging segments have been a focus. Researchers have analysed the capacity of diverging segments using empirical and simulation methods [2-3]. Other studies have also been conducted on level of service (LOS), traffic delay and operational characteristic [4-6]. In addition to the studies above, there were also researches on diverging segments' safety. Some researchers explored the contributing factors to crashes at freeway diverging locations [7-8], they discovered that AADT, lane-type configuration and speed are always tend to increase the severity of crashes at freeway diverging areas. The operating speed of diverging segments were also been studied [9-10], and linear regression model were adopted to predict the speed of diverging area. Studies using speed have been proven to be an effective way to understand the safety performance of road. Some researchers identified the relationship between crashes and speed [11-13]. Their researches demonstrated that the larger the variance of speed, the higher the crash rates. As for the speed safety of diverging segments, the linear regression model of speed was established and the safety level of speed was arrived at based on the 85th percentile individual speed difference in diverging segments [14].

From what have been mentioned above, it is not hard to conclude that there were numerous studies on speed and traffic safety at diverging segments respectively. However, with respect to speed safety for diverging segments, there were not enough studies. Hence, this study conduct speed safety analysis for diverging segments. The initial speed and the travel distance are considered in the regression model. Meanwhile, volume and weather conditions are used to revise the speed model developed. Exploring the connection between speed and safety would be helpful in finding hazardous diverging segments.

The sections are organized as follows. Section 2 first introduces the research methodology which is used in building the model and assessing the safety level of diverging segments. Section 3 presents the statistics analysis of speed collected. Section 4 demonstrates the regression model of speed at diverging segments. The speed safety evaluation result is showed based on material-unit in section 5. Finally, Section 6 summarizes the findings, conclusions and limitations of the paper.

2 Methodology

This study built a multivariable linear regression model to estimate the speed of vehicles at freeway diverging segments according to the statistics analysis of speed data collected. Linear regression allows multi-variables to be properly calibrated, and outputs are relatively easy to interpret. What is more important is that the assumptions of linear regression models are often suitably satisfied in practical applications [15].

In this study, vehicles are classified into heavy (wheel base is larger than 7m or power density is small or equal to 15kw/t) and small ones (the others). The operating speed model are established for heavy and small vehicles individually, the operating speed of vehicles at diverging segments is then arrived at according to the ratio of the speed for heavy vehicles and the small vehicles estimated.

The research assumes that the operating speed are jointly influenced by initial speed, travel distance, volume and weather factors. To be more specific, initial speed v_0 and travel distance L are put in the regression model, the others are used to revise the estimated model. Speed can be expressed as (1):

$$v=\beta_0+\beta_1 v_0+\beta_2 L+\varepsilon \qquad (1)$$

where ε follow a normal distribution with mean and standard deviation equal to 0 and σ, respectively. β_0 β_1 and β_2 are estimated constants. Linearity, homoscedastic disturbances and normally distributed disturbances should be checked to make sure that linear regression is appropriate.

In our study, speed v_0, speed difference d and coefficient of variation for speed cv are calculated according to the speed regression model built, which are assumed to be the indicators related to speed safety of diverging segments. Vague sets [16] surpass fuzzy sets when deal with uncertain information [17]. Thus vague sets are applied in this study to estimate the safety level of speed at diverging segments. Compared with traditional multi-objective decision methods, vague sets can effectively deal with uncertainty conditions. The comprehensive material-element can be calculated as (2):

$$v_{ij}=[t_{ij},1-f_{ij}] \qquad (2)$$

where v_{ij} is the vague value of object i with indicator j, t_{ij} represents for the true membership function and f_{ij} denotes the false membership function. In our study, all the indicators are supposed to be as smaller as they can, thus t_{ij} and f_{ij} are calculated as (3) and (4), respectively.

$$t_{ij}=(x_j^{\max}-x_{ij})\big/(x_j^{\max}-x_j^{\min}) \qquad (3)$$

$$f_{ij}=(x_{ij}-x_j^{mim})\big/(x_j^{\max}-x_j^{\min}) \qquad (4)$$

where x_{ij} denotes the value of object i with indicator j, $x_j^{\max}$ represents for the maximum value of indicator j of all objects, and $x_j^{\min}$ is the minimum value of indicator j of all objects. The essence of this process is normalization.

The weights of indicators are calculated by means of AHP. And similarities between the matter-element under test and the indicator of standard are computed as (5):

$$M_z(x,y_j) = 1-\frac{\left|t_x-f_x-t_{yj}+f_{yj}\right|}{8}-\frac{\left|t_x+f_x-t_{yj}-f_{yj}\right|}{4}+\frac{\left|t_x-t_{yj}\right|+\left|f_x-f_{yj}\right|}{8} \qquad (5)$$

where x represents for the indicator value for the matter-element under test, y_j is the indicator value for different levels. The comprehensive similarity is computed as (6):

$$d_j=\sum_{i=1}^{n} w_j M_{ij}(x_{in},y_{ij}) \qquad (6)$$

where d_j is used to illustrates the similarity between the indicator under test and the standard value, w_j is the weight for indicator j, $M_{ij}(x_{in},y_{ij})$ denotes the similarity between the matter-element under test and the indicator of standard. It is obvious that a larger similarity value indicates the safety level of speed.

3 The statistic characteristics

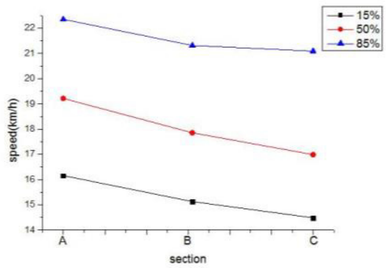
The research study the diverging segment of MaQun interchange of G42 in Nanjing, China. The speed data was extracted by Tracker based on aerial video imager collected. Three cross-sections (the diverge point C, the midpoint B and terminal point A) of datasets were screened from data extracted at the influence area of diverging segment. In this research, the segment is set as straight line for convenience, and the speeds are analysed and modelled for heavy vehicle and small vehicles(the others), respectively.

Descriptive statistics are useful way to understand the primary characteristics of speed. Take heavy vehicles as example, Table 1 provides speed information about the basic statistics for heavy vehicles. The statistics indicate that the speed of each cross section follows normal distribution. There seems little difference among the statistics for section A, B and C, which means central tendency of heavy vehicles' speed.

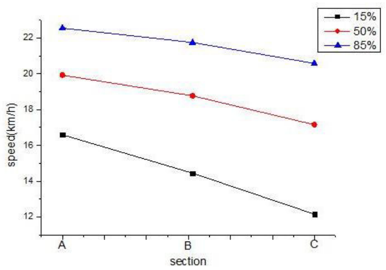
Table 1. The summary statistics of speed for heavy vehicles

Cross-section	A	B	C
Mean	19.172465	18.209627	17.412200
Std. deviation	2.7175877	2.7816214	2.9391556
skewness	-0.232	0.041	0.289
kurtosis	-0.494	0.702	-0.423
minimum	12.6778	12.3483	11.9281
maximum	24.0144	23.8396	24.4921
15th percentile	16.156235	15.127065	14.483093
50th percentile	19.217385	17.852405	16.986620
85th percentile	22.350810	21.313448	21.089265

The curves of speed with heavy vehicles and small vehicles are illustrated by Figure 2. The characters of the speed curve are as follows. First, it is obvious that the vehicle will decelerate when reaching the diverge point. Second, there appears dissimilarity in terms of speed range with heavy and small vehicles. Furthermore, it can be easily seen from Figure 2 that the speeds present a decreasing trend for all the vehicles. What is more important is that deceleration of different vehicles demonstrate different and that the deceleration distance are longer for the heavy vehicles in comparison to small vehicles.



a) Heavy vehicles



b) Small vehicles

Figure 2. The speed curve of vehicles

4 The regression model

4.1 Model estimation

A multivariable linear regression model is built to estimate the speed for heavy and small vehicles at diverging segment. Table 2 shows the parameter estimates of the regression estimated on the collected data for heavy vehicles.

It can be easily seen from Table 2 that this model contains a constant and two explanatory variables-the initial speed and travel distance. The signs of the estimated parameters are in line with expectation. Travel distance is with a negative coefficient, indicating that long distance might decreases the speed of heavy vehicles, which is easy to be understood. Meanwhile, long distance (L) also indicates of worse travel conditions, and then results in low speed of heavy vehicles. Initial speed v_0 is with positive coefficient which determines the operating speed. The two independent variables are statistically significant with the value of $|t| \geq 1.96$ under level of significance 5%. The value of R_{adj}^2 is 0.7325, which indicates that 73.25 percent of total variance can be explained by independent variables.

Table 2. The linear regression parameters of heavy vehicles

Variables	Coefficients	Std.	t-value	P>t
L	-0.0213	0.0016	-13.27	0
v_0	0.8233	0.0097	84.69	0
Cons	4.4756	0.1782	25.11	0

*Variable significant at 95% interval.

Linearity, homoscedastic disturbances and normally distributed disturbances are checked to make sure that linear regression is appropriate. Thus the regression model of speed can be expressed as (7):

$$v_h = 4.4756 + 0.8233 v_0 - 0.0213 L \qquad R_{adj}^2 = 0.7325 \quad (7)$$

where v_h denotes the operating speed of heavy vehicles, v_0 and L are of the same meaning defined before.

The regression models of small vehicles can be expressed as (8) by the same method.

$$v_s = 3.2417 + 0.8474 v_0 - 0.0268 L \qquad R_{adj}^2 = 0.6806 \quad (8)$$

where v_s represents for the operating speed for small vehicles. The explanatory variables are of the same meaning as noted before.

4.2 Model calibration

Volume and weather factors are found to have significant impact on the actual operating speed of vehicles. Volume is with negative impact, indicating that high volume might decrease the speed of vehicles. Wet road surface condition reduces the speed of vehicles. It leads to smaller friction and results in longer braking distances. Meanwhile, vehicles are more likely to lose control under wet road condition, thus the driver tends to decelerate for safety consideration.

The speed model can be rewritten as (9) with consideration of volume and weather conditions:

$$v = v_0 + v_v + v_0 f \quad (9)$$

where v represents for the actual operating speed of vehicles, and v_0 is the estimated speed by regression model, v_v denotes the speed reduction because of high volume and f denotes the coefficients of speed reduction due to road surface conditions.

The speed reductions for freeways with volume and weather condition are shown as Table 3 to Table 4, respectively.

Table 3. The speed reduction of different LOS

LOS	v/c	Speed reduction	
		Heavy vehicles	Small vehicles
A	<0.25	0	0
B	<0.65	3	4
C	<0.75	5	8
D	1	-	-

Table 4. The speed reduction of weather condition

Road surface condition	Dry	Wet
f	0	0.15

5 Safety evaluation

5.1 Evaluation criteria

Transportation is a complex, diverse and stochastic system involving people, vehicles, roads and traffic management. And operating speed of vehicles is influenced by all these factors. Research shows that average speed (v), speed difference (d) and the coefficient of variation (cv) are assumed to have straightforward influence on speed safety of vehicles [18]. Speed difference is the difference between the average speed and the design speed. The coefficient of variation is the ratio of the standard deviation and the average speed.

In this paper, three indicators are used to evaluate the safety level for vehicles according to Specifications for Highway safety audit [19] and the speed safety criteria of highway [20], the criteria of vehicles developed with the consideration of traffic circumstances, which is shown as Table 5.

Table 5. The criteria for speed safety

Indicators	Level I	Level II	Level III
v	v £ 20	20 < v ? 40	v > 40
d	d £ 10	10 < d ? 16	d >16
cv	cv £ 10	10 < cv ? 15	cv >15

5.2 Safety evaluation

In our study, vague sets are applied to estimate the safety level of speed for vehicles. There are several steps to follow to arrive at the safety level of vehicles speed. First, the comprehensive material-element can be calculated by (2). Second, the weights of indicators are calculated by means of AHP. Furthermore, similarities between the matter-element under test and the indicator of standard are computed by (5). Finally, the comprehensive similarity is computed by (6) and the safety level of speed is confirmed.

5.2.1 Vague sets

The research studies the speed safety level of the diverging segment of MaQun interchange of G42 in Nanjing, China. The diverging segment is of three lanes and one auxiliary lane with mainline design speed 60 km/h.

According to the regression model and speed reductions, the average operating speed is calculated at 20.0175km/h (the ration of heavy vehicles and small ones is calculated at 17.1372%), the speed difference is 39.9825 km/h and the coefficient of variation is 14.1745%. The comprehensive material-units and the vague sets are calculated by (2), as is shown in Table 6 and Table 7, respectively.

Table 6. The comprehensive material-units

Indicators	Level I	Level II	Level III	Indicators under test
v	(0,20)	(20,40)	(40,60)	20.0175
d	(0,10)	(10,20)	(20,60)	39.9825
cv	(0,10)	(10,15)	(15,60)	14.1745

Table 7. The comprehensive vague sets of material-units

Indicators	Level I	Level II	Level III	Indicators Under Test
v	(0,0.333)	(0.333,0.667)	(0.667, 1)	(0.3336，0.3336)
d	(0,0.167)	(0.167, 0.333)	(0.333,1)	(0.6664，0.6664)
cv	(0,0.167)	(0.167, 0.25)	(0.25, 1)	(0.2362，0.2362)

5.2.2 The weights of indicators

The weights of indicators are calculated by means of AHP, which is presented as Table 8.

Table 8. The indicators weights

Indicators	v	d	cv
weights	0.139	0.332	0.528

5.2.3 The similarities

The similarities between the matter-element under test and the indicator of standard are computed by (5). The results are presented as Table 9. It is obvious that a larger similarity value indicates the safety level of speed. The safety levels of average speed, speed difference and the coefficient of variation are Level II, Level III and Level I, respectively.

Table 9. The indicators similarity

Indicators	M_1	M_2	M_3
v	0.874813	0.874906	0.708438

d	0.687688	0.771063	0.833219
cv	0.902754	0.771063	0.833219

5.2.4 The safety level

Table 10 provides information about the comprehensive similarity computed by (6). The similarity is 0.8150, 0.7847 and 0.8266 for Level I, Level II and Level III, respectively. Which indicates the speed safety level of diverging segment is level III. Hence, the result found in this study is that the safety level of diverging segment in terms of speed is not the optimal. And measures like speed limit should be taken to manage the speed of diverging segments.

Table 10. The comprehensive similarity for different speed safety levels

Level	Level I	Level II	Level III
Comprehensive Similarity	0.8150	0.7847	0.8266

6 Conclusion

Freeways diverging segments may easily become bottlenecks for traffic safety. One effective way to improve the safety of diverging segments is to study the speed safety with the objective of identifying the hazardous diverging segments and reducing the risk of diverging segments by traffic control and management.

In order to provide effective predictors for diverging segments' speed, this research study the diverging segment of MaQun interchange of G42 in Nanjing, China. The speed data was extracted by Tracker based on aerial video imager collected. The regression linear model shows that initial speed and travel distance are important factors with negative and positive coefficient, respectively. Besides the two factors, volume and weather factors are used to calibrate the operating speed. Based on the proposed model, the safety level of diverging segments can be identified using vague sets. The results show that the safety level of diverging segments in terms of speed is not the optimal, and measures like speed limit should be taken to manage the speed safety of diverging segments.

There are limitations of this study. The regression model considered only two variables regardless of significant GOF. The studied segments are straight lines, other geometric designs do not vary too much. More geometric designs can be explored in the future.

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References

1. *Highway Capacity Manual* (TRB, Washington, D.C. , 2010)
2. Bertini, R. L., Hansen, S., and Bogenberger, K. *Empirical analysis of traffic sensor data surrounding a bottleneck on a german autobahn,* TRR, 97(2005)
3. Leong, L.V., Mahdi, M. B., and Chin, K. K. *Microscopic simulation on the design and operational performance of diverging diamond interchange.* TRP, **6**,198 (2015)
4. Wu, N., and Lemke, K. *A new model for level of service of freeway merge, diverge, and weaving segments.* Procedia - Social and Behavioral Sciences, **16**, 151 (2011)
5. Newell, G. F. *Delays caused by a queue at a freeway exit ramp*, **33**, 337 (1999)
6. R. Qiu. *Research on traffic stream characteristics of off-ramp junction in the interchange*. (Doctoral dissertation, Southeast University,2006)
7. Chen, H., Liu, P., Lu, J. J., and Behzadi, B. *Evaluating the safety impacts of the number and arrangement of lanes on freeway exit ramps.* AAP. J., **41**,543(2009)
8. Mergia, W. Y., Eustace, D., Chimba, D., and Qumsiyeh, M. *Exploring factors contributing to injury severity at freeway merging and diverging locations in ohio*. AAP. J., **55**,202, (2012)
9. Z. Zhang, X. Hao, and W. Wu. *Research on the running speed prediction model of interchange ramp*. Procedia - Social and Behavioral Sciences, **138**,340 (2014)
10. W. Wu. *Research on the operating speed prediction model of interchange ram*p (Doctoral dissertation, Beijing Technology University, 2009)
11. Solomon, D. *Accidents on main rural highways related to speed.* (1964)
12. Liu, G., and Popoff, A. *Provincial-wide travel speed and traffic safety study in saskatchewan*. TRR, **1595**, 8 (1997)
13. Baruya, B. *Speed-accident relationships on european roads.* Trl Annual Research Review. (1999)
14. H. Xu. *Research on level of service of safety for freeway diverging area based on speed consistency.* (Doctoral dissertation, Harbin Institute of Technology, 2011)
15. *Statistical and Econometric Methods for Transportation Data Analysis.* (A CRC Press Company, Washington, D.C. 2003)
16. W.Gau. *Vague sets.* IEEE Transactions on Systems Man and Cybernetics, **23**,610(1993)
17. W. Yan. *The application of entropy multipurpose decision method at evaluation of biding*. **36**,98(2004)
18. B. Luo. *Safety appraisal and improvement measures of two-lane roads based on operating speed*. (Doctoral dissertation, Beijing, 2008)
19. *Specifications for Highway safety audit.* (China communication press, 2015)
20. Y. Yang. *Study on the speed of public transport in mountainous cities*. (Doctoral dissertation, Chongqing Jiaotong university, 2014)