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An Evaluation of Highway Work Zone Impact Factors on Driving Safety Using Complicated Indexes Based On Traffic Simulation System

Jiao Yan [1,a], Chi Zhang [2,b], Meng-Hua Ding [3,c], Yichang (James) Tsai [4,d]

[1,2,3] School of Highway, Chang' an University, Xi'an City, China

[4]School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, USA ; School of Highway, Chang'an University, Xi'an City, China

[a]yanjiao5210@yahoo.cn, [b]zhangchi@chd.edu.cn, [c]987691640@qq.com, [d]james.tsai@ce.gatech.edu

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Abstract: There are quite a number of complicated factors that can affect driving safety on freeway work zone during reconstruction, for example, traffic volume, driver compliance rate (which means drivers who follow the posted speed limit), slope gradient, HGV rate and so on. This article uses the popular traffic simulation software VISSIM to simulate different situations. The results show that the safety of Upstream Transition Area and the place where speed limit signs locate are the lowest. It is recommended that speed limit signs should not be located that much, and cars and HGVs need to be more careful when merging into the Upstream Transition Area, and lower their speeds if necessary. Most important, compliance rate plays an important role in safety measures, and this provides a solid foundation for traffic control and management.

Introduction

Nowadays freeways are playing a more and more important role in the field of road transportation, but after a period of usage, freeways need to be maintained and reconstructed frequently in order to keep road and its facilities in good conditions. But during the reconstruction, accidents that happened at work zone gradually increase, and the aftermaths are severe, so the safety of work zone is gaining more and more attention. It is very necessary and pressing to improve the road safety of freeway work zone.

Bing Wu [1] defining the riskiness of traffic accidents and using Grey Forecasting Theory to analysis the riskiness of traffic accident during highway maintenance. And it shows the forecasting model has relatively satisfactory precision. Bai [2] investigated the characteristics of fatal crashes and risk factors, used the four-step approach to analysis them, and proposed the unique crash characteristics and risk factors in the work zones and recommended improvements on work zone safety. And in Li [3] and Biao Wu's [4] study, the concept of using crash severity index (CSI) for work zone safety evaluation was proposed and a set of CSI models were developed through the modeling of work zone crash severity outcomes. Pei [5] analysis spot speed investigation data of fourteen freeways in China, regression models are established between 85th percentile speed and CCRs, 15th percentile speed and CCRs, and it put forward reasonable speed limit suggestion values. Most of the studies are using real collected data, and make a prediction of the risk level. It takes a lot of time and money to collect these data, and with the development of traffic engineering, microscopic simulation is widely used in generating data. After we got the traffic data of vehicles, we need some safety measures to evaluate the safety of work zone.

Sivanaga S et al. [6] developed a safety surrogate measure, minimum safety distance equation (MSDE) to quantify the safety of the performance of the VSL system. Qing-Fang Wu use VISSIM as platform and MSDE as the safety measure to analysis the speed scheme in unfavorable weather, Calculate and determine the value of speed limit for visual range as 80m and 20m. Wang [7] utilizes traffic simulation software VISSIM to carry on the simulation of traffic operation with variety of speed-limiting conditions.it use MSDE and CV as the evaluation indexes, and a better speed-limiting program and a better location of speed-limiting signs are obtained. Tang [8] compared the road safety researches home and abroad, choosing the minimum safety distance equation and the speed of the equivalent standard deviation coefficient of variation as an evaluation index, but it doesn't have any case to check the accuracy of it. Huang [9] analysis the advantages and disadvantages of the accident statistics analysis and TCT. It uses 'look ahead distance' as a study case to evaluate the safety of the road, and use MSDE as the safety measure. Yi-Hu Wu [10] concluded that the accident rate is most correlative with speed deviation (CV), so the speed deviation is the key factor which has influence on traffic safety. From the literature home and abroad, we can see MSDE and CV are widely used, and the accuracy of them is good, but they don't use them to evaluate the impact factors on driving safety in work zone.

There are quite a number of complicated factors that can affect traffic safety, and it's difficult to evaluate their influences with math methods. In this study, we use the popular traffic simulation software VISSIM to simulate different situations, and use combined z-scores of MSDE and CV to evaluate their influences on traffic safety.

Methods

We choose minimum safety distance equation (MSDE Eq. 1) [6] and coefficient of speed standard variation (CV Eq. 2) [7] as safety measures.

$$MSDE = 1.47(V_L \times h - V_F \times PRT_F) + \frac{V_L^2 - V_F^2}{30(f \pm g)} \quad (1)$$

$$cv = \frac{\text{Speed standard deviation}}{\text{average speed}} \quad (2)$$

Where, V_L= Velocity of the lead vehicle in mph, V_F = Velocity of the following vehicle in mph, PRT_F = Perception and reaction time of the following vehicle in seconds (default of 2.5 seconds is used), f = friction factor, g = grade, h = time headway in seconds.

For the purpose of MSDE calculation in the simulation runs, it is assumed that the speed of the leading vehicle measured "h" seconds ago remains constant. This assumption is a limitation and was to be made since the existing point detection systems can only measure the speed of a single vehicle on top of the detection zone.

In order to evaluate the safety at work zone properly, and eliminate the influence of the factors' units, we combine normalized z-scores of MSDEs and CVs. The z-scores are then obtained using the formula (Eq. 3) below.

$$z = \frac{X - X_1}{\sigma} \quad (3)$$

Where, X is the "MSDE" value for speed, X_1 is the average of "MSDE" values for the different slope gradients, compliance rates, traffic volumes and HGV rates, and σ is the standard deviation of the "MSDE" values. And so does CV. It is noted that the bigger MSDE the safer is, while the bigger CV means less safety. Thus, -1 is multiplied to CV z-scores before adding it to the MSDE z-scores. Then bigger combined value will indicate better performance in terms of safety.

Case study

For the development of the postulated test-bed network a four lane rural highway (two lanes in each direction) was considered. The work zone is implemented by closing one of the lanes in a direction for a length that corresponds to the activity area. Lengths of different sections are set according to the JTG30-2004, Safety Work Rules for Highway Maintenance. This work zone configuration consists of 6 essential parts: Warning Area, Upstream Transition Area, Buffer Space, Activity Area, Downstream Transition Area, Termination Area. Fig. 1 shows the work zone layout for the configuration mentioned above.

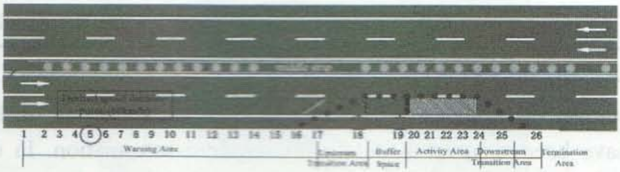

Fig. 1 Work zone layout for the configuration

1) Coding the test network in VISSIM

This section describes the coding of the postulated network in VISSIM as shown in Fig. 1.

Six sections mentioned above are presented by three 'links' and four connectors. Link 1,link 2 and link 3 measuring 1700m,550m, 60m, respectively are used to create the network in VISSIM. These links represent four different sections of the work zone –Warning Area (the first 100m is not the study section, and it is used to generate vehicles), Buffer Space, Activity Area and the Termination Area. Each link apart from Buffer Space and Activity Area consists of two lanes. The bottom lane of link 2 is closed to all the traffic making it the Activity Area. The connectors form the Upstream and Downstream Transition Area. Upstream Transition Area represents the merging area of the work zone.

'Detectors' are used to detect the presence of vehicles. They are also used to obtain the speed and headway information. In order to plot the curves of MSDE and CV well, we set 26 'data collection points' on the links and connectors. They are deployed on the above lanes as shown in Fig. 1 about every 100 meters.

Two 'vehicle classes', namely compliant and non-compliant vehicles are defined within the simulation. Each class consist of 30% HGVs mix. Different compliance rates are achieved by varying the percentage of these two classes within the 'traffic composition' in VISSIM simulation program.

VISSIM use 'desired speed distributions' to define the speed range of vehicles. If not hindered by other vehicles a driver will travel at his/her desired speed. 100km/h and 80km/h are set for cars and HGVs respectively.

'Desired speed decision points' are used to alter initially assigned vehicles' desired speed distributions. They represent speed limit signs in real life. Four speed decision points are placed within the network. The first two are located at a distance of 500 meters of link 1, and the altered speed is 60km/h. And the last two are located at the 30 meters of link 3. This is the point vehicles are removed from the limited speed.

2) Range of different factors

When building a simulation model of studying a section of highway, we need to input road conditions such as slope gradient, as well as traffic conditions such as traffic volume, HGV Rate and Compliance Rate. The bigger the parameter ranges, the more helpful to analyze the study' conclusion. According to practices and this article's research demand, we constrained the range of this study.

The ranges of the parameters are shown as Table1.

Table 1 Simulation parameter values of road and traffic conditions

Traffic and road conditions	simulation parameter values
HGV Rate /%	0, 10, 20, 30, 40, 50
Slope Gradient/%	0, 1, 2, 3, 4, 5
Compliance Rate/%	100, 90, 80, 70, 60, 50

3）Determine the Sample Size

We get a large number of data after simulation, and we don't need all of them. Data from the simulation output have been reduced to obtain the required information. In order to ensure the experimental data effectively and save the calculation time, the required minimum sample size should be determined. According to the principle of mathematical statistics, and to meet the corresponding confidence interval, we use the formula below.

$$n=\left(\frac{\sigma K}{E}\right)^2 \qquad (4)$$

Where, n ——minimum sample size; K ——Level of confidence coefficient, 3 is used in this text; σ ——standard deviation of the estimated sample, 8 is used in this text. E ——the permissible error value of observation speed (km/h), depends on the required speed accuracy, 2km/h is used in this text.

So, take the numbers above into Eq.4, and

$$n=\left(\frac{\sigma K}{E}\right)^2=\left(\frac{8\times 3}{2}\right)^2=144$$

So we take 200 as the minimum sample size.

Data analysis

Contrast test for HGV rate: input vehicle volume of 750 vehicles per hour (vph), the desired speed of car is100km/h, and HGV is 80km/h, slope gradient is 0%. HGV rate of 50%, 40%, 30%, 20%, 10%, 0% have been used. HGV rates' influence on MSDE is shown as Fig. 2, and on CV is shown as Fig. 5.

Contract test for Slope Gradient: input vehicle volume of 750 vph, the desired speed of car is 100km/h, and HGV is 80km/h, HGV rate is 30%. Slope gradient of 0%, 1%, 2%, 3%, 4% and 5% have been used. Gradients' influence on MSDE is shown as Fig. 3, and on CV is shown as Fig. 6.

Contract test for Compliance Rate: input vehicle volume of 750 vph, the desired speed of car is 100km/h, and HGV is 80km/h, HGV rate is 30%. Slope gradient is 0%. Compliance rates of 50%, 60%,70%,80%,90% and 100%have been used. Compliance rates' influence on MSDE is shown as Fig. 4, and on CV is shown as Fig. 7.

1) MSDE

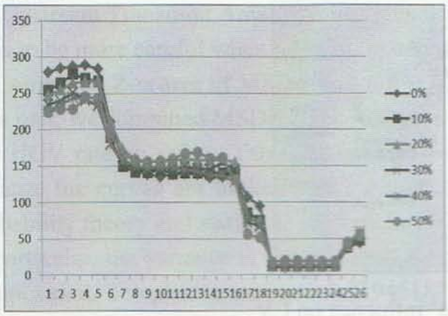

Fig.2. HGV Rates' influence on MSDE

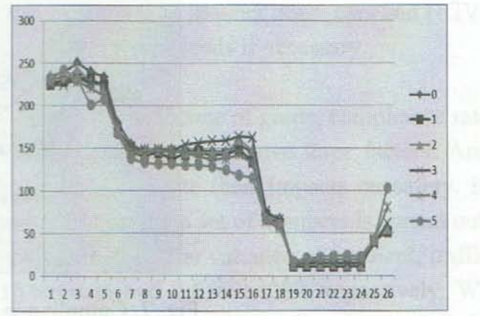

Fig. 3. Gradients' influence on MSDE

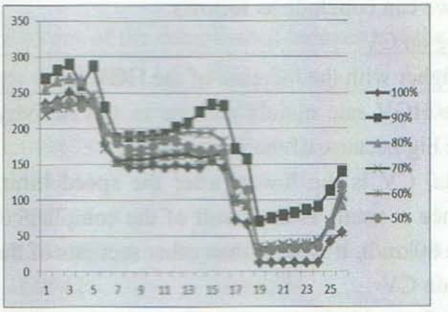

Fig. 4.Compliance Rates' influences on MSDE

From the curves above, we can conclude as follows:

① The 18th data collection point is the lowest point of MSDE, because the 18th point is located at the Up Stream Transition Area. Cars and HGVs are merging at the transition areas, most of the vehicles need to change their lanes in order to merge into the single lane, thus large number of traffic conflicts happened. And this is very dangerous and can cause traffic conflicts.

② The curves in Fig. 2 and Fig. 3 almost coincide, while curves in Fig. 4 are discrete, and these curves don't have any regularity to follow. It seems that higher compliance rate means bigger MSDE. While the blue curve shows that when all the drivers follow the posted speed limit sign, the value of MSDE is low. It is because the formula of the MSDE has some limited conditions as explained above. But we can also conclude that compliance rate plays an important role in safety measures, lower compliance rate causes traffic conflicts between cars and HGVs.

2) CV

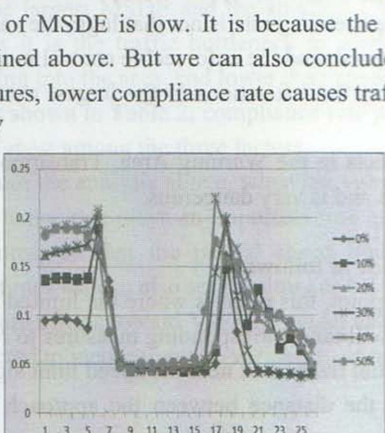

Fig. 5. HGV Rates' influences on CV

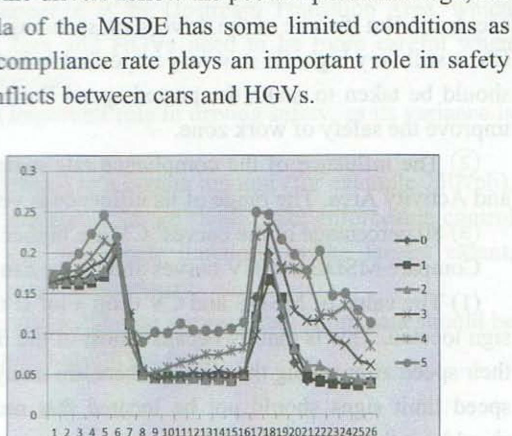

Fig. 6. Gradients' influence on CV

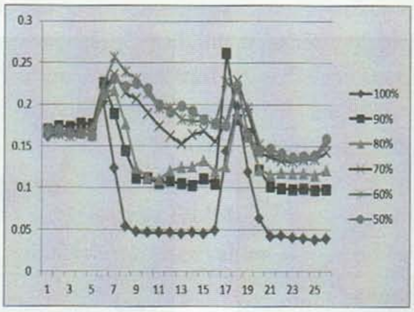

Fig. 7. Compliance Rates' influence on CV

From the curves above, we can conclude as follows:

(1) HGV Rates' influence on CV

① The value of CV is higher with the increase of the HGV rate.

② The influence of the HGV rate mainly reflects in the Activity Area, the speed difference between cars and HGVs are big because of the narrow road.

③ In the Warning Area, CV is the lowest after the speed limit, and the curves are almost coincide, the speed difference is small as the result of the compliance rate is 100%, and all of the vehicles' desired speeds are 60km/h, it is safer than other sections of the work zone.

(2) Gradients' influence on CV

① The value of CV is higher with the increase of the slope gradient, and the growth rate is more and more big.

② The influence of the gradient mainly reflects in the Activity Area, which means that it is more dangerous to close the road to do the maintenance work if the grade is higher than 2%. We can see from the curves that, CV change little when the grade is lower than 2%, and change a lot when the grade is higher than 2%. If the work zone is on the steep slope, strengthened safety protection measures should be taken, and Activity Area can be split into several parts if necessary.

(3) Compliance Rates' influence on CV

① The value of CV is higher with the decrease of the compliance rate, and the growth rate is more and more small. That is to say, if vehicles follow the limited speed totally, there are little accidents. But if some of the drivers are speeding, and the speeding rate is not that high, the value of CV is still very high. So it is very important to limit the speed, and the enforceable control measures should be taken to make the posted speed limit sign play their functions to the largest extent, to improve the safety of work zone.

② The influence of the compliance rate mainly reflects in the Warning Area, Transition Area and Activity Area. The range of its influence is very wide and is very dangerous.

③ 80 percentage of the curves' CV are higher than 0.1.

Compare MSDE and CV curves above, we can conclude as follows:

(1) The value of MSDE and CV drop a lot at the 5th point, this point is where the limited speed sign located. This is mainly because most of the drivers will take corresponding measures to reduce their speed after seeing the sign, so there are many potential dangerous near the speed limit sign. So speed limit signs should not be located that much, or the distance between the approach signs should not that big.

(2) The largest MSDE and the smallest CV are happened at the 18th point, this point is located at the Upstream Transition Area, which means it is the traffic bottleneck in work zone, cars and HGVs need to be more careful when merging into the area, and lower their speeds if necessary.

3) Combined Z-scores of MSDE and CV

This part, we combined MSDE and CV together, to evaluate the influence of grade, compliance rate and HGV rate on safety. Table 2 below shows influences caused by the above three factors. And because the curves are broken lines, we use the variance to evaluate their impacts on safety. In probability theory and statistics, the variance is a measure of how far a set of numbers is spread out. In particular, the variance is one of the moments of a distribution. The variance of gradient, traffic composition, compliance rate are 2.519461882, 2.133103606 and 2.656964089 respectively. We can see that compliance rate plays an important role in safety measures. And gradient is the second.

Table 2 Combined z-scores of the complicated indexes and the variances of them

Object	Slope Gradient	HGV Rate	Compliance Rate
1	1.637217	2.458377	-0.789370136
2	1.149433	1.535734	3.319111771
3	1.384844	-1.04677	0.613620878
4	0.099701	-1.50065	-1.668992591
5	-2.31699	-0.75794	-0.900320157
6	-1.9542	-0.68876	-0.574049766
Variance	2.519461882	2.133103606	2.656964089

Results and Conclusions

The objective of this study was to evaluate the influence of different factors' impact on diving safety. We use VISSIM to simulate different situation, parts of the conclusions are shown below.

The value of MSDE and CV drop a lot at the limited speed sign located. This is mainly because most of the drivers will take corresponding measures to reduce their speed after seeing the sign, so there are many potential dangerous near the speed limit sign. So speed limit signs should not be located that much, or the distance between the approach signs should not that big.

The largest MSDE and the smallest CV are happened at the Upstream Transition Area, which means it is the traffic bottleneck in work zone, cars and HGVs need to be more careful when merging into the area, and lower their speeds if necessary.

As shown in Table 2, compliance rate plays an important role in driving safety, as its variance is the biggest among the three factors.

From the analysis above, when the volume is defined to a certain amount (for example 750vph), compliance rate plays an important role in safety measures. So we should take enforceable control measures, so that the posted speed limit sign can play their functions to the largest extent, sometimes we can also set monitors or "electronic eyes" if necessary.

More efforts toward VISSIM model calibration and validation are required. More data should be collected to incorporate the variability of traffic conditions on the field.

Acknowledgements

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