Accident Analysis and Prevention 119 (2018) 176–187

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

# Freeway crash risks evaluation by variable speed limit strategy using real-world traffic flow data

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ARTICLE INFO

*Keywords:*
Crash risk
Crash likelihood
Spatial-temporal perspective
Congestion
Variable speed limit
Freeways

ABSTRACT

The primary objective of this study is to evaluate the real-time crash risk of freeways by using real-world traffic flow data. The crash risk expressed as the potential crash likelihood is assessed under variable speed limit (VSL) and without VSL, in which both spatial correlation between different sites and temporal similarity are contained. Traffic flow data of Whitemud Drive network (WMD) in Canada is used to perform the relevant analysis, including VSL implementation analysis, traffic flow similarity analysis, crash risk and congestion analysis. Analytical results demonstrate that the average traffic flow under VSL schemes 1, 2, 3 and 4 are highly correlated from spatial-temporal perspective. The crash likelihoods and congestions under these VSL schemes are greatly improved. The best VSL control scheme, the most dangerous area and time, together with the most congested station of WMD are eventually determined. Subsequently, a *t*-test is employed to examine the significance of these results. *t*-Test results suggest that the improvement degree between crash risk and congestion under the best VSL control scheme show a difference, i.e., the best VSL control scheme can reduce the crash risk of moderate risk area more than high risk area, while it may have a larger melioration on the most congested area than the relatively uncongested area. Finally, these results are considered to have the potential reference in the mitigation of WMD traffic issues.

## 1. Introduction

The past decades have witnessed a rapid increase in road crash risks that related to actual crash accidents or potential crashes. Generally speaking, these risks may not only contribute to the casualties and loss of property, but also cause a serious congestion. Because the travel speed in freeways is so high that once an incident occurs, the vehicle speed upstream may be sharply dropped, which will result in a traffic collapse. According to the federal highway administration of the United States, traffic accidents account for about 25% of the traffic congestions (Federal Highway Administration, 2005). Hence, the crash risk of road network has become a critical problem with considerable implications in recent years. How to effectively evaluate the risk is of vital importance for reducing the potential crash of freeways, which will play an indispensable role in the modern traffic management system. Crash risk evaluation of freeways get involved in identifying the potential risk locations and analyzing the impact of these risks on freeway networks. An efficient evaluation of crash risk can help the road managers to grasp the overall operation of the traffic condition and provide a basis for preventing traffic accidents or congestions.

Several studies have been conducted on the crash precursor of freeways. Islam and El-Basyouny (2015) performed a before-after safety evaluation with the object to evaluate the safety effects of reducing residential posted speed limit (PSL). Result showed that PSL reduction was found effective in reducing crashes. Kwak and Kho (2015) developed crash risk prediction models for identifying crash precursors based on loop detector data. The genetic programming was used to predict and evaluate the crash risk. The Model results showed that the traffic flow characteristics leading to crashes are differed by segment type and traffic flow state. Xu et al. (2016) investigated the predictability of crash risk models that were developed by using high-resolution traffic data. The predictability was defined as the crash probability given the crash precursor model. The conclusion suggested that crash risk modeling should focus on improving the predictability of crash risk models, not the prediction accuracy. Fang et al. (2016) utilized the eigenvectors of freeway loop data spatiotemporal schematic to predict the real time

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https://doi.org/10.1016/j.aap.2018.07.009
Received 10 February 2018; Received in revised form 21 June 2018; Accepted 3 July 2018
Available online 21 July 2018
0001-4575/ 

crash. The eigenvectors and eigenvalues of the spatiotemporal schematics were extracted to represent the traffic flow situation before the crash occurrence, and then a logistic model was used to identify the precursors. Results showed that both the eigenvectors and eigenvalues can significantly impact the accident likelihood.

Recently, artificial intelligence (AI) is gradually used in the evaluation and prediction of road safety. Halim et al. (2016) studied the AI technique for improving driving safety and predicting the vehicle crash, in which statistical methods were used to predict the accidents. Several machine learning methods were increasingly carried out as well in crash risk evaluation (Yu and Abdel-Aty, 2013; Sun and Sun, 2014; Qu et al., 2017; You et al., 2017; Basso et al., 2018). For example, Yu and Abdel-Aty (2013). proposed a support vector machine (SVM) approach for evaluating the real-time crash risk, and the model's predictive abilities that barely involved in other models were investigated. Sun and Sun (2014) adopted Bayesian method to analyze the accident risk and then evaluate the predictability of crash risk. Finally, the method was proved to be feasible. Qu et al. (2017) studied freeway rear-end crash potential predictors by using SVM technique. The relationship between rear-end crash occurrences and traffic conditions was explored through using historical loop detector data. Finally, it was confirmed that the SVM technique in rear-end crash prediction analysis has superior performance. You et al. (2017) presented an optimized crash prediction model on freeways with over-sampling techniques based on SVM. The results indicated that SVM classifiers improved the prediction accuracy. Basso et al. (2018) developed accident prediction models based on disaggregate data that were captured by free-flow toll gates with automatic vehicle identification. Three methods (i.e., Random Forest, SVM and Logistic Regression method) were proposed to identify the strongest precursors of accidents. The result showed that the best model accurately predicted 67.89% of the accidents with a low false positive rate of 20.94%.

Goodall (2017) analyzed the secondary crash occurrence of freeways, and integrated incident timelines and traffic volumes. Results showed that 9.2% of all vehicle crashes were secondary to another incident and that 6.2% of these crashes were tertiary to another primary incident. Wang et al. (2016) identified the secondary accidents based on traffic shock waves, and the study associated a secondary accident with its primary accident and the shock waves from it. Results showed the secondary accidents in California interstate freeway accounted for 1.08% of the total crashes, and this was much lower than the result of Goodall et al.

As an emerging method of traffic control, VSL control is increasingly popular in traffic management. VSL can improve both the congestion and crash risk of freeways. Plenty of studies have been presented in the regard of VSL to improve congestion (Bertini et al., 2006; Lu et al., 2011; Pu et al., 2012; Yang et al., 2013; Sun et al., 2014; Cao et al., 2015; Yang et al., 2015; Li et al., 2017). However, compared with the issue of VSL to relieve traffic congestion, the safety problem under VSL control might be more noteworthy. Because the traffic safety is directly related to people's vital interests (e.g., injuries, deaths, or loss of property), and this is supposed to be more important than people's interests in traffic congestion (e.g. delay increase, emissions increase, etc.). Several literatures revealed that significant efforts have been conducted to evaluate the potential and real-time crash risk (Lee et al., 2006; Abdel-Aty et al., 2006; Allaby et al., 2007; Abdel-Aty et al., 2009a; Mannering, 2009; Yu and Abdel-Aty, 2014). The afore-mentioned studies on VSL mostly aimed at single traffic congestion or crash risk. The integrated researches of the two aspects are relatively limited, and the relevant literatures are less than that of single study of traffic congestion or crash risk. For instance, Khondaker and Kattan (2015) presented a VSL control algorithm for simultaneously maximizing the mobility (this aimed to improve congestion), safety (this aimed to improve crash risk) and environmental benefit in a connected vehicle environment, total travel time (TTT) and time to collision (TTC) were used to measure the mobility and safety respectively. Their result indicated that VSL control can achieve a 20% reduction of TTT and 6%–11% improvement of TTC. Wang and Cheng (2017). studied the control and setting locations of variable speed limit signs, and the accident rate reduction (this aimed to improve crash risk) and traffic congestion improvement were the main objectives. Lyu et al. (2017) established a comprehensive VSL control model for reducing both travel delay (this aimed to improve congestion) and potential crash risk at freeway work zones. The objective was to minimize the operational cost by reducing the total travel delay and potential crash rate. Abdel-Aty et al. (2009b) proposed the application of VSL to improve safety and efficiency of freeways. The VSL algorithms were applied to analyze the crash risk and travel time, and it was found that VSL was effective to reduce crash risk and average travel time in some certain cases.

As discussed above, several aspects were relatively limited. For example, almost no researcher has comprehensively analyzed both the potential crash and congestion from spatial-temporal perspective, i.e., previous studies only studied a single aspect of traffic congestion or crash, or the analysis of crash risk and congestion is performed based on a single spatial (Korter, 2016) or temporal (Michalaki et al., 2016) perspective. In the meantime, the crash risk evaluation conducted in previous studies are primarily based on the simulation data, and these evaluations were limited compared with the researches that based on real-world data. Accordingly, the study conducted in the current paper fills these knowledge gaps. This study evaluates both congestion and crash risk from the spatial-temporal perspective. The actual traffic flow data was used to evaluate the impact of VSL control on congestion and crash risk. The results may be more objective and practical in comparison with those similar studies conducted in previous researches. Moreover, a *t*-test is employed to analyze the significance of the result, which makes it more convincing.

The remainder of this paper is structured as follows. Section 2 introduces the study corridor. Section 3 lists the data source. Section 4 presents the crash risk model. Section 5 describes the VSL implementation and traffic flow similarity. Section 6 proposes the evaluation of crash risk and congestion of WMD based on spatial-temporal perspective, and the *t*-test is also contained in this section. Section 7 makes a discussion about the results. Finally, section 8 shows a brief review of this paper and proposes the future research direction.

## 2. Study corridor

Whitemud Drive (WMD) is the study corridor of this paper, and it is an urban freeway in Edmonton, Alberta, Canada. The total length of WMD is about 28 km, and the basic speed limit was 80 km/h (it was the static posted speed limit). As the experiment road, WMD was equipped with loop detectors in its mainline and ramps. The specific study segment is the westbound direction of WMD, which is located between 122 St and 159 St (see Fig. 1). The length is about 11 km, and comprised of 12 ramps, 9 loop detector stations, and 7 video cameras. In addition, the directional average annual daily traffic (AADT) was up to approximately 100,000 vehicles. The 9 loop detector stations were all located on the mainline of WMD, and each of which consisted of dual-loop detector groups in each travel lane. These detectors and cameras measured traffic flow data every 20 s. Besides, the existing VSL control was adopted to alleviate traffic congestion at peak hours, and the data records under VSL control spans from 16:00 to 19:00 with different speed limits (i.e., 30 km/h to 80 km/h). The speed limits for other periods were 80 km/h. Fig. 1 shows the basic composition of the study corridor. In this paper, we only analyze the mainline of WMD, i.e., the stations of VDS 1018, VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS 1035, VDS 1036, VDS 1016, and VDS 1007.

## 3. Data source

The original data is obtained from a data sharing website called Open ITS, and the real-time data only contains the traffic flow, speed,

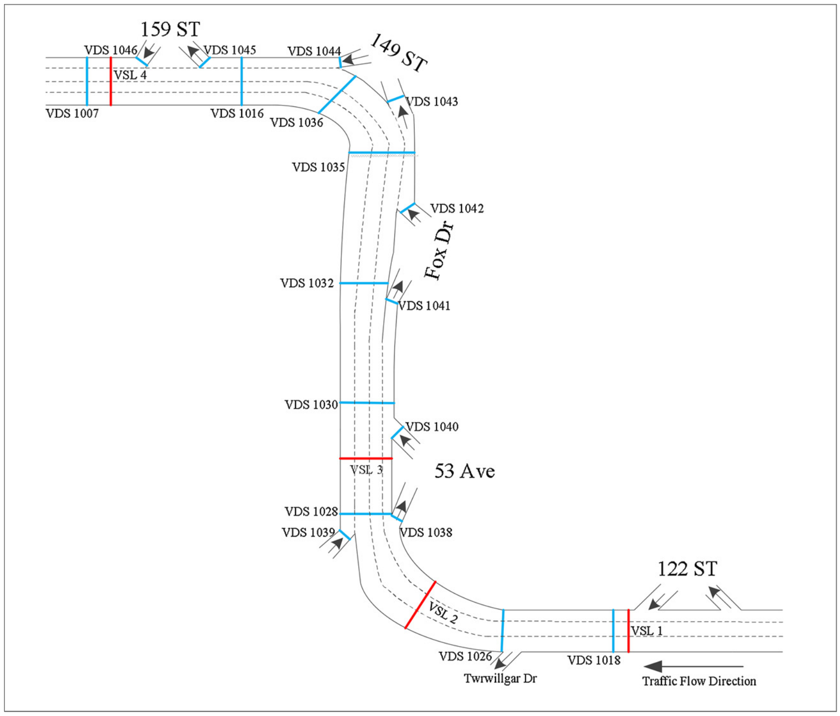


**Fig. 1.** Composition of the study corridor.

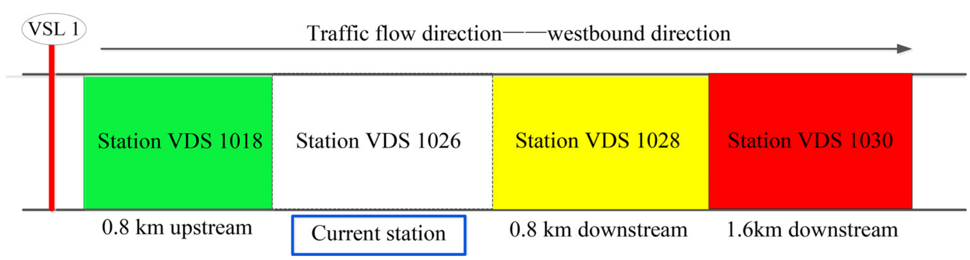


**Fig. 2.** Distribution of VDS 1026 and its upstream and downstream.

and occupancy of WMD. The data were collected from 7:00 to 19:00 on August 11 to 20, 2015 (August 13 to 20 denoted the VSL control time, while the others were without VSL control). Raw data collection interval was 20 s, but it is 5 min in this study. According to Eq. (1), there are such current stations as VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS 1035, VDS 1036, thus the crash likelihoods of these stations need to be evaluated. Other stations are recognized as the upstream or downstream of the current stations. For instance, if the current station is VDS 1026, then VDS 1018 is approximately considered as 0.8 km upstream of this station, and VDS 1028 and VDS 1030 are approximately considered as 0.8 km and 1.6 km downstream of this station. Under this circumstance, the crash likelihoods of these stations can be calculated according to Eq. (1). For a convenient analysis, the current station and its upstream and downstream are separately taken to calculate the crash likelihood. Fig. 2 shows the distribution of VDS 1026 (current station) and its upstream and downstream. Other current station analyses are performed as the same way as VDS 1026.

In Fig. 2, the distances between VDS 1026 and its upstream (VDS 1018) and downstream (VDS 1028 and VDS 1030) are not 0.8 km or 1.6 km exactly but the approximations. As illustrated in Fig. 2, VSL 1 was implemented upstream of VDS 1018, and in this case, the real traffic flow condition and crash risk are different to the case of without VSL. Four VSL (e.g., VSL 1, 2 3, 4) were implemented in the study corridor (see Fig. 1). The period to set VSL control was the peak hours (i.e., from 16:00 to 18:00) on August 13 to 20, 2015. The data detected from 16:30 to 18:30 is selected to analyze the crash likelihood in this study. The VSL implements are the existing schemes by the local traffic authorities to relieve congestion of peak hours. Thus, the setting of VSL (including the locations and speed limits) has been determined, i.e., VSL 1 was implemented upstream of VDS 1018, VSL 2 was implemented downstream VDS 1026, VSL 3 was set between VDS 1038 and VDS 1040, and then VSL 4 was located upstream VDS 1007 (see Fig. 1). In a word, the four VSL were all implemented nearby the ramps or curves, which might be attributed to the complex traffic condition of these locations. The frequent shunt and confluence of vehicles can not only lead to traffic congestion, but also contribute to the increasing of crash risk. Therefore, this study aims primarily to analyze the potential risks of the stations (e.g., VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS 1035, VDS 1036) apart from the traffic congestion analysis (this analysis is secondary compared with the crash risk analysis).

## 4. Crash risk model

Several scholars have analyzed the crash risk of freeways. (e.g., Sun et al., 2014; Wang et al., 2016). The risk models were created differently in these studies, but they all contained the specific accident information such as the accident rate, accident type, fatalities or injuries. Nevertheless, the crash risk studies that based on traffic flow information were presented relatively few, only limited researches were conducted in this regard (i.e., Abdel-Aty et al., 2006; Lee et al., 2006; Xu et al., 2016). Abdel-Aty et al. (2006) proposed a crash likelihood of freeways based on the simulated traffic flow data. In their studies, the crash risks were separately developed for a moderate-to-high-speed and low-speed traffic speed regime, and the threshold for separating the two regimes was 37.5 mph (Abdel-Aty et al., 2005, 2006). When the speed was beyond 37.5 mph, a moderate-to-high-speed was considered. Contrariwise, it was the low-speed. The model based on moderate-to-high speed and low-speed expressed as Eqs. (1) and (2), respectively.

$$C_i = -0.93423o_i + 1.\ 145840_{i+2}\text{—}0.\ 22878s_{i+2}\text{—}0.\ 10055q_{i+1} + 0.\ 5932q_{i-1} \tag{1}$$

Where $C_i$ is the crash likelihood at station $i$ (current station), $o_i$ is the log of average occupancy at station $i$ of 5–10 min before the time interest, $o_{i+2}$ is the log of average occupancy 1.6 km downstream of the current station $i$ of 10–15 min before the time interest, $s_{i+2}$ is the standard deviation of traffic flow 1.6 km downstream of the current station $i$ of 5–10 min before the time interest, $q_{i+1}$ is the average traffic flow 0.8 km downstream of the current station $i$ of 5–10 min before the time interest, and $q_{i-1}$ is the average traffic flow 0.8 km upstream of the current station $i$ of 10–15 min before the time interest.

$$C_i = -2.64827v_i + 0.8884v_i' + 1.339660_{i-1} + 0.977660_{i+2} - 0.43603s_{i+2} \tag{2}$$

Where $C_i$ is crash likelihood at station $i$ (current station), $v_i$ is the log of the standard deviation of average speed at station $i$ of 5–10 min before the time interest, $v_i'$ is the log of the standard deviation of average speed at the current station $i$ of 10–15 min before the time interest, $o_{i-1}$ is the log of average occupancy 0.8 km upstream of the current station $i$ of 5–10 min before the time interest, $o_{i+2}$ is the log of average occupancy 1.6 km downstream of the current station $i$ of 10–15 min before the time interest, $s_{i+2}$ is the standard deviation of traffic volume 1.6 km downstream of the current station $i$ of 5–10 min before the time interest.

Eqs. (1) and (2) can provide a method to evaluate the potential crash risk of freeways based on the simulated traffic flow data, but Abdel-Aty et al pointed out that this measure can only be used to compare the crash risk at the current station. Because the crash likelihood in Eqs. (1) and (2) can somehow denote the potential crashes of vehicles with traffic flow data rather than the specific crash information. Given that our research data contains only traffic flow information (e.g., traffic volume, speed and occupancy), it might be difficult to evaluate the crash risk according to those models that related to specific crashes. Thence we have to explore the potential crash risk based on current traffic flow data. Additional, the study corridor of our study is similar to Abdel-Aty's study. Meanwhile, there may be little differences between the simulated environment and real-world situation of freeways, because the weather, incidents all can be added to the simulation environment with the fast development of the advanced microsimulation technology. According to the above analyses, the effect of VSL on improving the potential crash likelihood in Abdel-Aty's research may also be suitable in our study. So, Abdel-Aty's model is introduced into this study to evaluating the crash risk. In the meantime, this study can also be considered as a verification of Abdel-Aty's method in WMD. In other words, this study aims to prove the data transferability between the Abdel-Aty's study and ours, and before this, several literatures have introduced the transferability study of the crash risk models between different freeway corridors (i.e., Sawalha and Sayed, 2006; Khondakar et al., 2010; Shew et al., 2013; Xu et al., 2014). Furthermore, it is not limited to evaluate one station that was available in Abdel-Aty et al. (2006), and this evaluation will cover several stations (i.e., VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS 1035, VDS 1036) from spatial-temporal perspective, which might show more important or specific results.

On account of the speed in WMD was beyond 37.5 mph, it can be regarded as the moderate-to-high-speed, and then the crash likelihood can be calculated by Eq. (1). It should be noted that the crash likelihood can not necessarily indicate that the actual crashes occur but measure the potential risk of collision between vehicles. Thereby the model may not present the real crashes, while it indeed provides a macroscopic approach for evaluating the crash risk of WMD.

## 5. VSL implementation and traffic flow similarity analysis

### 5.1. Implementation of VSL

The VSL control schemes related in this study have been implemented by the traffic authorities of Alberta in 2015, so the locations of VSL are fixed (see Fig. 1). Four VSL implemented in WMD, and normally the corresponding speed limits can be dynamically adjusted according to the actual traffic flow conditions. While in fact, only VSL 1 can really display the actual variable speed limits (changing from 80 km/h to 30 km/h over time), others VSL control schemes, i.e., VSL 2, 3 and 4 showed the static speed limits (80 km/h) all the time, and this is informed by the VSL report from Open ITS. Therefore, the VSL schemes involved in this paper are mainly the dynamic speed limits of VSL 1. Generally, the speed limit changes at a stepladder trend (Yang et al., 2015), the VSL control schemes in different days were various according to the actual speed limit data from Open ITS. In other words, the specific speed limits from August 13 to 20 were distinct. Four VSL schemes performed at VSL 1 are presented in our study, and they correspond to the four days, i.e., August 13 (VSL scheme 4), 17 (VSL scheme 3), 18 (VSL scheme 2) and 19 (VSL scheme 1). Fig. 3 shows these VSL schemes.

All the speed limits were the integer times of 10, like 80 km/h, 70 km/h, etc. Fig. 3 shows that the speed limits of the four schemes are the same with the static speed limit (80 km/h) before 16:45. As time goes on, the traffic flow become heavy, especially in the section of on-ramps, the conflicts between vehicles were increasing, then the crash risks may increase, so the speed limits begin to decrease to different degrees for ensuring a smooth transition of vehicles. From 17:00 to 17:40, these VSL schemes presented a stepladder change to varying degrees (i.e., the speed limits under these cases are decreased and increased repeatedly), which may explain that this period was the peak hour of WMD, and the traffic conditions were so complex that the vehicles slow down and speed up back and forth. After that, the speed limits of these VSL schemes show a stabilization trend in different degrees and then will maintain this state for a while, which suggests that the traffic flow may be smooth in this period. As illustrated in Fig. 3, VSL scheme 1 shows the biggest speed change, and the lowest speed limit is 30 km/h, which is lower than other 3 schemes (the lowest speed limits of VSL scheme 2, 3, 4 are 50 km/h, 50 km/h and 60 km/h respectively). Moreover, the peak hour of VSL scheme 1 ends later than other schemes, i.e., the speed limit of VSL scheme 1 can return to 80 km/h after 18:24 (the finish time of VSL scheme 2, 3 and 4 are 17:37, 17:41, and 17:49 respectively). On the basis of this analysis, it can be inferred that the speed limit of VSL scheme 1 changes the most and lasts the longest time, so this seems to work best for the reduction of crash risks. This inference will be proved in Section 6.1.1.

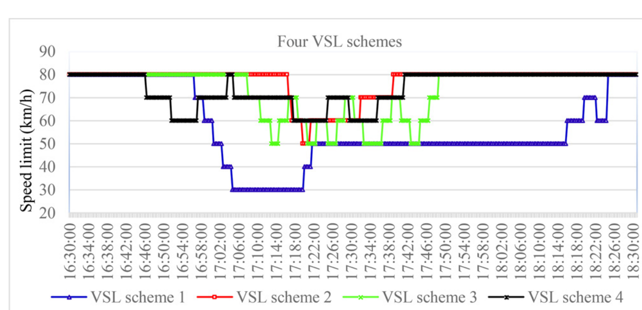


**Fig. 3.** Four VSL schemes.

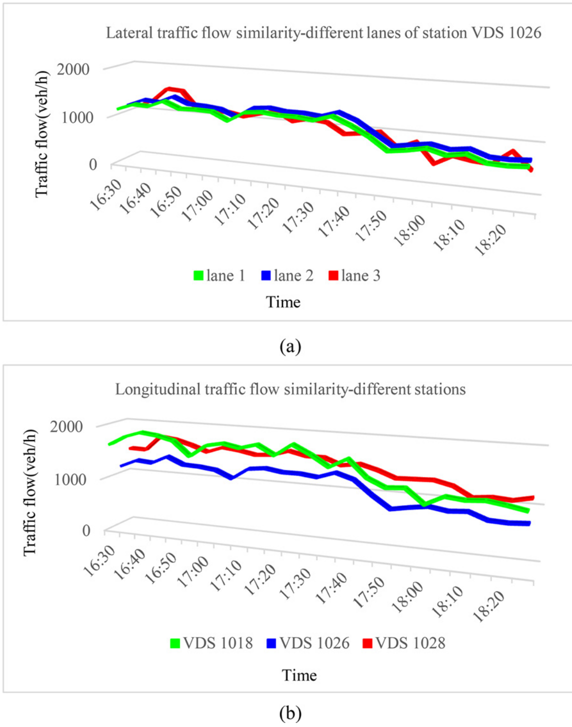


**Fig. 4.** Analysis of traffic flow similarity (a. lateral similarity; b longitudinal similarity).

## 5.2. Analysis of traffic flow similarity

Traffic flow data owns dynamic and similar characteristics. The similarity characteristic presents in both spatial and temporal aspects. In spatial perspective, adjacent lanes (lateral aspect) of current stations and its upstream and downstream (longitudinal aspect) are contained. The temporal perspective consists of different days such as August 13, 17, 18 and 19.

The correlation coefficient $R$ is used to analyze the traffic flow similarity. $R$ has a certain range, i.e., $|R| \le 1$, $|R| = 1$ is completely linear relationship, $|R| = 0$ are not linear. $|R| < 0.3$ represents the weak linear relationship, $0.3 < |R| < 0.5$ is the moderate linear relationship, then $0.5 < |R| < 0.8$ denotes the significant linear relationship. Finally, $0.8 < |R| < 1$ represents the high linear relationship.

### 5.2.1. Similarity analysis from spatial perspective

Different lanes of the current station (station VDS 1026 is taken as an example) are selected to make the lateral analysis. Then the average traffic flow of the three lanes of every 5 min from 16:30 to 18:30 are listed in Fig. 4(a). The average traffic flow of station VDS 1026 and its upstream (VDS 1018) and downstream (VDS 1028) are analyzed to present the longitudinal similarity, as shown in Fig. 4(b). The changes of average traffic flow in lateral and longitudinal aspects are regular, and they are basically present the similar trend (i.e., at lateral, the traffic flow is similar; at longitudinal, it is also similar), which can be seen from Fig. 4(a), (b). Besides, the quantitative results of these similarities are confirmed by the correlation coefficients, as shown in Tables 1 and 2. Tables 1 and 2 shows that the correlation coefficients of

**Table 1**
Correlation coefficients of traffic flow (veh/h) at lateral aspect in VDS 1026.

| R | lane 1 | lane 2 | lane 3 |
|---|---|---|---|
| lane 1 | 1.0000 | 0.9984 | 0.8126 |
| lane 2 | 0.9984 | 1.0000 | 0.8820 |
| lane 3 | 0.8126 | 0.8820 | 1.0000 |

**Table 2**
Correlation coefficients of traffic flow(**veh/h**) at longitudinal aspect.

| R | VDS 1018 | VDS 1026 | VDS 1028 |
|---|---|---|---|
| VDS 1018 | 1.0000 | 0.8996 | 0.9092 |
| VDS 1026 | 0.8996 | 1.0000 | 0.8827 |
| VDS 1028 | 0.9072 | 0.8827 | 1.0000 |

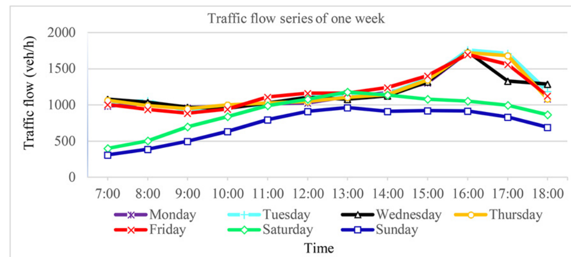


**Fig. 5.** Traffic flow of one week at VDS 1018.

the lateral and longitudinal aspects are all higher than 0.8, which corresponds to high correlations. So, the traffic flow from spatial perspective shows the similar characteristic, which has also been proved by Wang et al. (Wang et al., 2017). The other stations like VDS 1028, VDS 1030, VDS 1032, and etc., also present the same similarities.

### 5.2.2. Similarity analysis of temporal perspective

Seven different days (i.e., August 13 to 19, and they correspond to Thursday, Friday, Saturday, Sunday, Monday, Tuesday, and Wednesday, respectively) are selected to describe the temporal similarities of traffic flow. Then the average traffic volume from 7:00 to 18:00 processed by one hour are listed in Fig. 5 and Table 3 (VDS 1018 is taken as an example). Due to the fact that August 13, 17, 18, 19 represent the four VSL control schemes (see Fig. 3) that are closely related to our study, the correlation coefficients $R$ of these days are also calculated for further explaining the correlations.

Fig. 5 illustrates that the average traffic flow among weekdays seems to be more similar in a large degree. Meanwhile, the average traffic flow between Saturday and Sunday (weekend) also explains the highly similar characteristic. But the similarities between weekdays and weekend are relatively small. These distinctions may result from the different travels between weekdays and weekend. People need to work on weekdays, so the travels may be more frequent, thus the traffic flow and their similarities between these days are also big. On weekend, people tend to have a rest at home or reduce their use of motor vehicles. Therefore, the average traffic flow is relatively small, and the similarities between these days and weekdays are also small. But the internal similarity of weekend (i.e., the similarity between Saturday and Sunday) is large. The correlation coefficients ($R$) in Table 3 also demonstrate this argument, i.e., $R$ between weekdays are all beyond 0.85, which suggests that the traffic flow (veh/h) between these days are highly correlated. But $R$ between weekdays and weekend are relatively small. For example, $R$ between Friday and Saturday is 0.5933, and $R$ between Friday and Sunday is 0.6735, which indicates that Friday is significantly correlated with Saturday and Sunday. In the same way, Monday, Tuesday, Wednesday and Thursday present the moderate correlation relationship with Saturday and Sunday, because $0.3 < |R| < 0.5$ in these cases.

The above analysis is efficient in VDS 1018, and it is also feasible in other stations of WMD. For example, we take VDS 1028, 1030, 1032, 1035, and 1036 into consideration, then the correlation coefficients are shown in Tables 4–8. Considering that Monday (VSL scheme 3), Tuesday (VSL scheme 2), Wednesday (VSL scheme 1) and Thursday (VSL scheme 4) are the days of the four VSL control schemes that closely related to our study, only these days are considered in this part.

**Table 3**
Correlation coefficients of traffic flow (veh/h) at VDS 1018.

| R | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| Monday | 1 | 0.9855 | 0.8652 | 0.9932 | 0.9473 | 0.4235 | 0.4948 |
| Tuesday | 0.9855 | 1 | 0.9063 | 0.9878 | 0.9526 | 0.3990 | 0.4832 |
| Wednesday | 0.8652 | 0.9063 | 1 | 0.8810 | 0.8994 | 0.3615 | 0.4529 |
| Thursday | 0.9932 | 0.9878 | 0.8810 | 1 | 0.9559 | 0.3968 | 0.4765 |
| Friday | 0.9473 | 0.9526 | 0.8994 | 0.9559 | 1 | 0.5933 | 0.6735 |
| Saturday | 0.4235 | 0.3990 | 0.3615 | 0.3968 | 0.5933 | 1 | 0.9905 |
| Sunday | 0.4948 | 0.4832 | 0.4529 | 0.4765 | 0.6735 | 0.9905 | 1 |

**Table 4**
Correlation coefficients of traffic flow (veh/h) at VDS 1028.

| R | VSL scheme 4 | VSL scheme 3 | VSL scheme 2 | VSL scheme 1 |
|---|---|---|---|---|
| VSL scheme 4 | 1 | 0.9722 | 0.9721 | 0.9593 |
| VSL scheme 3 | 0.9722 | 1 | 0.9574 | 0.9591 |
| VSL scheme 2 | 0.9721 | 0.9574 | 1 | 0.9853 |
| VSL scheme1 | 0.9593 | 0.9591 | 0.9853 | 1 |

**Table 5**
Correlation coefficients of traffic flow (veh/h) at VDS 1030.

| R | VSL scheme 4 | VSL scheme 3 | VSL scheme 2 | VSL scheme 1 |
|---|---|---|---|---|
| VSL scheme 4 | 1 | 0.9881 | 0.9961 | 0.9349 |
| VSL scheme 3 | 0.9881 | 1 | 0.9864 | 0.9093 |
| VSL scheme 2 | 0.9961 | 0.9864 | 1 | 0.9257 |
| VSL scheme 1 | 0.9349 | 0.9093 | 0.9257 | 1 |

**Table 6**
Correlation coefficients of traffic flow (veh/h) at VDS 1032.

| R | VSL scheme 4 | VSL scheme 3 | VSL scheme 2 | VSL scheme 1 |
|---|---|---|---|---|
| VSL scheme 4 | 1 | 0.9806 | 0.9153 | 0.9700 |
| VSL scheme 3 | 0.9806 | 1 | 0.9101 | 0.9870 |
| VSL scheme 2 | 0.9153 | 0.9101 | 1 | 0.9320 |
| VSL scheme1 | 0.9700 | 0.9870 | 0.9320 | 1 |

**Table 7**
Correlation coefficients of traffic flow (veh/h) at VDS 1035.

| R | VSL scheme 4 | VSL scheme 3 | VSL scheme 2 | VSL scheme 1 |
|---|---|---|---|---|
| VSL scheme 4 | 1 | 0.9675 | 0.9922 | 0.9776 |
| VSL scheme 3 | 0.9675 | 1 | 0.9746 | 0.9794 |
| VSL scheme 2 | 0.9922 | 0.9746 | 1 | 0.9816 |
| VSL scheme 1 | 0.9776 | 0.9794 | 0.9816 | 1 |

**Table 8**
Correlation coefficients of traffic flow (veh/h) at VDS 1036.

| R | VSL scheme 4 | VSL scheme 3 | VSL scheme 2 | VSL scheme 1 |
|---|---|---|---|---|
| VSL scheme 4 | 1 | 0.9811 | 0.9737 | 0.9000 |
| VSL scheme 3 | 0.9811 | 1 | 0.9816 | 0.9250 |
| VSL scheme 2 | 0.9737 | 0.9816 | 1 | 0.9381 |
| VSL scheme 1 | 0.9000 | 0.9250 | 0.9381 | 1 |

The purpose is to verify that the average traffic flow (veh/h) of these days are also highly correlated in other stations apart from VDS 1018. If the average traffic flow of these days is all highly corrected, then they can be approximately regarded equal within the margin of error. In other words, the traffic volume of these days can be equal to the that of the same day in this case. As shown in Tables 4–8, the correlation coefficients among Monday (VSL scheme 3), Tuesday (VSL scheme 2), Wednesday (VSL scheme 1) and Thursday (VSL scheme 4) are rather high and they are all close to 1. For this reason, the average traffic flow (veh/h) of these days can be close to the consistent, and they are almost equal. Thus, VSL schemes 1 to 4 can be recognized as four different VSL control strategies of one day, and only in this case, the subsequent study can be meaningful.

After the highly positive verification about the similarity ($0.8 \le |R| \le 1$), the four different VSL schemes of different days can be regarded as the actual VSL schemes of one day. This consideration is performed for a convenient comparison about the crash risk and congestion under VSL (VSL schemes 1–4) and without VSL of the same day, and it will be conducted in the subsequent section.

## 6. Evaluation of crash risk and congestion

### 6.1. Analysis of crash likelihood with and without VSL

Abdel-Aty et al (2006). evaluated the effect of VSL to improve safety under simulation environment, and the variables like speed limits and the locations of VSL can be adjusted according to their research demand under this environment (these variables can formulate different VSL schemes). While in our study, the experiment environment is the real freeway network and real-time traffic flow data, and the speed limits and VSL locations are also fixed. Hence, we regard the four existing VSL control schemes (i.e., average crash likelihood of VSL schemes 1 to 4 implemented on August 13, 17,18 and 19) and without VSL scheme (average crash likelihood of August 11, 12) as our comparison schemes. Moreover, crash risks of different stations from the spatial-temporal perspective are analyzed. The crash risks presented as crash likelihoods are evaluated in different cases in our study (e.g., VSL scheme 1 to 4 and without VSL), and this aims to identify crash risk degree of different stations and then find the best VSL control scheme.

#### 6.1.1. Determination of the best VSL control scheme

The studied stations like VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS 1035, and VDS 1036 denote the spatial aspect. Then the average crash likelihoods based on Eq. (1) in these stations from 16:30 to 18:30 are presented in Fig. 6, in which the horizontal axis is time (i.e., 16.0, 16.5, 17.0, 17.5, 18.0, 18.5 denotes the time of 16:00, 16:50, 17:00, 17:50, 18:00, 18:50), and the vertical axis is the average crash likelihood.

The average crash likelihoods in Fig. 6 denote the potential collisions of WMD. Five schemes, i.e., without VSL, VSL control schemes 1 to 4 are performed to reflect the different collision degrees under these schemes. The crash likelihoods of VDS 1026, VDS 1028 and VDS 1035 under without VSL control are almost equal to that of VSL control schemes 1, 2, 3 and 4 before 16: 30 (see Fig. 6 (a), (b), (e)), because the traffic situation of these stations may be similar during this period, and the effect of VSL control has not yet worked. But as time goes, the traffic situations become changeable, and then the VSL control schemes start to work obviously. Then the crash likelihoods of these stations become various, and especially from 16:30 to 17:00, and 17:30 to 18:00, the crash likelihoods of VSL schemes 1 to 4 are all lower than that of without VSL. As a result, the crash risks of VDS 1026, VDS 1028 and VDS 1035 are all reduced under VSL control. However, compared with

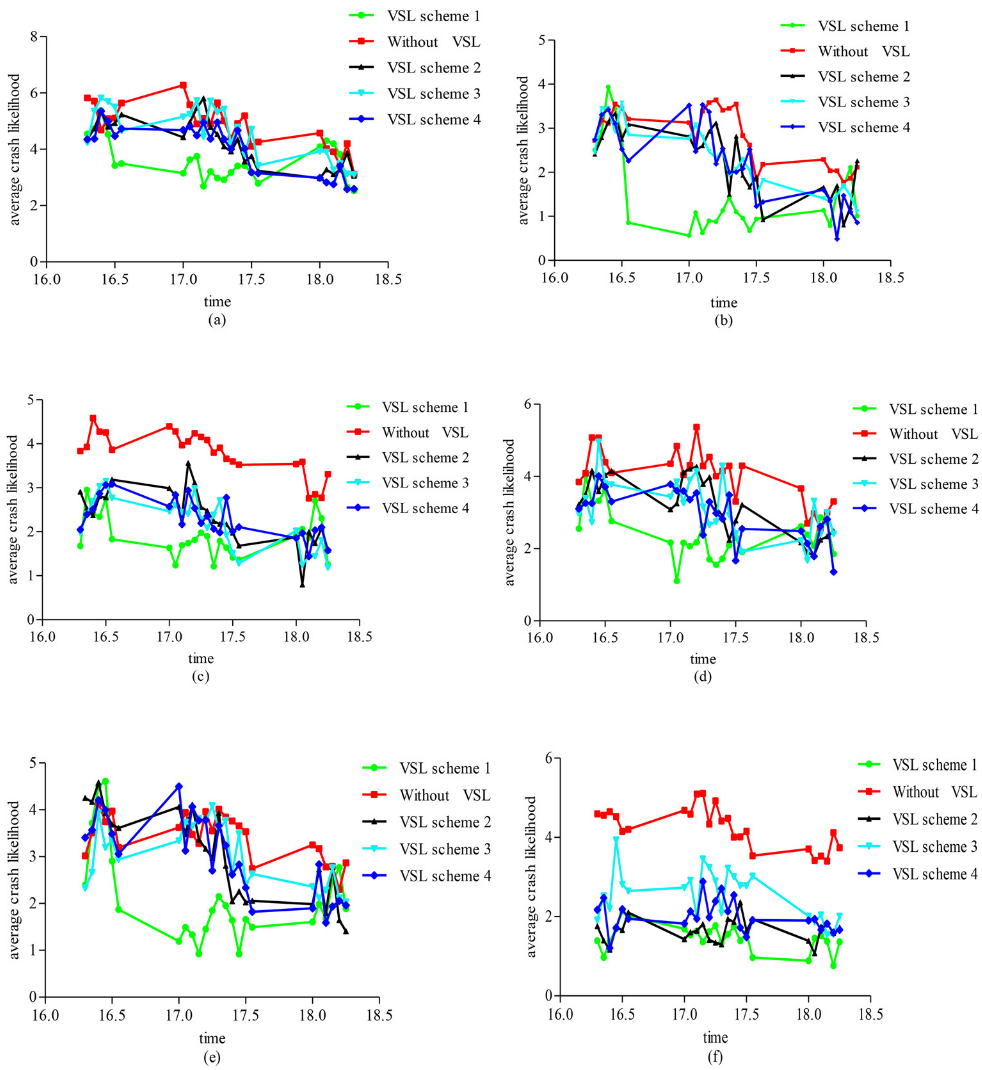


**Fig. 6.** Average crash likelihood of different stations (a. VDS 1026; b. VDS 1028; c. VDS 1030; d. VDS 1032; e. VDS 1035; e. VDS 1036).

VDS 1026, VDS 1028 and VDS 1035, the crash likelihoods of VDS 1030, 1032 and 1036 under VSL control schemes 1 to 4 are obviously lower than that of without VSL from the beginning to end (see Fig. 6(c), (d), (f)). This is mainly because of the reason of the huge difference of traffic situations in these stations from 16:30 to 18:30.

Besides, different VSL schemes also show various crash likelihoods. Generally, the crash likelihood of VSL scheme 1 is the lowest, and the rest VSL schemes (VSL schemes 2, 3, 4) show the approximate crash likelihoods in most stations of WMD except for VDS 1036 (in this station, the crash likelihoods of VSL scheme 3 is higher than VSL scheme 2 and 4). The average crash likelihood under VSL scheme 1 in VDS 1026 is 3.58, which decreases by 25.73%, 15.57%, 22% and 11.39% respectively compared with that of without VSL (average crash likelihood is 4.82), VSL scheme 2 (average crash likelihood is 4.24), VSL scheme 3 (average crash likelihood is 4.59), and VSL scheme 4 (average crash likelihood is 4.04). Similarly, this decreasing is also embodied in other stations of WMD. Thus, the inference in Section 5.1 is proved, i.e., VSL scheme 1 outperforms other VSL schemes in decreasing the potential crash risk of WMD. Additionally, it is proved that Abdel-Aty's method also shows positive effect in this study, for the crash likelihood of WMD are greatly reduced under VSL control, and this result aligns with previous research (Abdel-Aty et al., 2006). Thus, Abdel-Aty's model is validated preliminarily to be effective in WMD.

In order to further evaluate the transferability of the model, some indicators related to speed variance (see Eq. (2)) are also proposed to analyze the crash likelihood of WMD, which may be the additional supplementary to prove the model transferability between Interstate 4 (in Abdel-Aty et al., 2006) and WMD. The same data used to generate the crash likelihood of Fig. 6 were processed to meet the applicable conditions for Eq. (2), then the crash likelihood under low-speed condition (i.e., the speed is lower than 37.5mph) is obtained (see Fig. 7). These results show that the crash likelihoods are not reduced by VSL strategies under low speed condition, i.e., the crash risk may be not significantly changed under VSL strategies and without VSL. These results are also consistent with Abdel-Aty et al. (2006), so this may further illustrate the model feasibility of our research in some degree.

### *6.1.2. Identification of crash risk from spatial-temporal perspective*

The effect of VSL to improve crash risk of WMD has been analyzed in Section 6.1.1, and the best VSL control scheme (i.e., VSL scheme 1) has been determined. Then the crash risk identification from spatial-temporal perspective is evaluated in this part, i.e., the crash likelihoods of different stations at different time are evaluated to identify the most dangerous place and time of WMD. This is performed under the known conditions, i.e., the condition of VSL scheme 1 and without VSL. The heat maps are proposed to show the crash likelihood distributions. Fig. 8 intuitively shows these distributions.

Several kinds of colors are displayed in the distribution of crash likelihood. Red denotes high risk, and under this condition, the traffic flow may be serious and the crash likelihood is large. The darker the

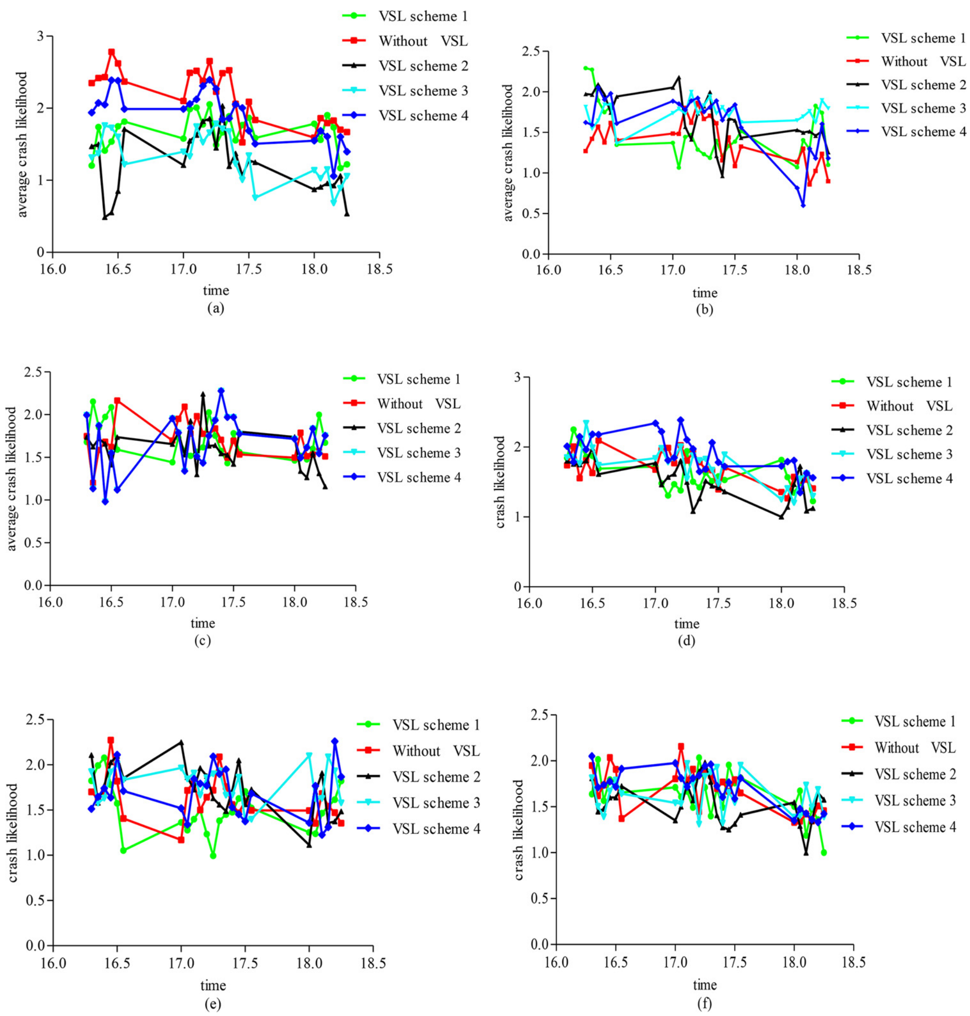


**Fig. 7.** Average crash likelihood of different stations (a. VDS 1026; b. VDS 1028; c. VDS 1030; d. VDS 1032; e. VDS 1035; e. VDS 1036) under low-speed condition.

color, the greater the risk. Yellow represents the moderate risk, and this color is also distributed in different shades of depth, and under this condition, the traffic flow may be not very heavy. Finally, green is the safest state with the lowest crash likelihood, in which the traffic flow may be fluent. Significant differences of crash likelihood are observed at different stations (see Fig. 8(a)). The color of VDS 1026 is the deepest, and then followed by VDS 1036, VDS 1032, VDS 1030, VDS 1035 and VDS 1028. This also indicates that the order of crash risk should be: VDS 1026 > VDS 1036 > VDS 1032 > VDS 1030 > VDS 1035 > VDS 1028, so the most dangerous and safest station of WMD might be VDS 1026 and VDS 1028 respectively. The following are the analysis about this order.

VDS 1026 is close to Terwillgar Dr (an off-ramp in WMD, see Fig. 1), and vehicles leaving from it will cause some conflicts, which can lead to the increasing of crash risk. Besides, this station is also located downstream of VSL 1, and only VSL 1 can make a changeable speed limits from 80 km/h to 30 km/h, which improves the traffic situation downstream and ensures the smooth transition of vehicles (this indirectly reflect that the traffic condition of VDS 1026 is somehow serious). Other VSL just show the static speed limits. So due to this reason, VDS

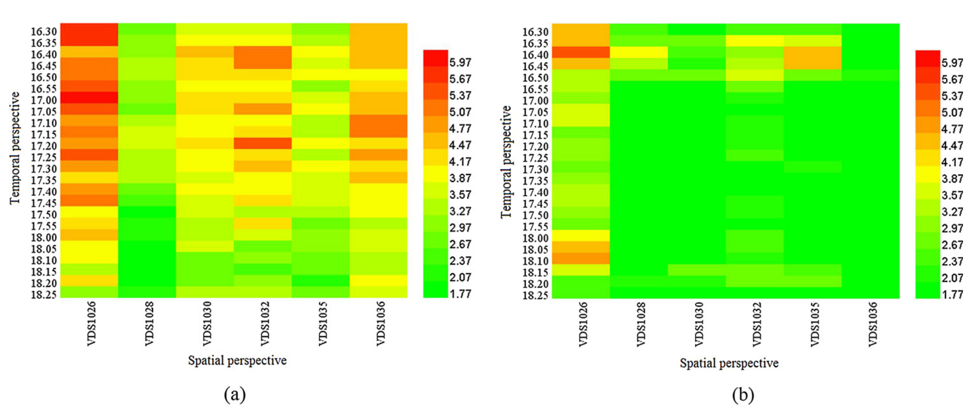


**Fig. 8.** Crash likelihood distributions under VSL scheme 1 and without VSL (a. without VSL; b. VSL scheme 1).

l018 and VDS l026 should be the riskiest areas. VDS 1028 is located between the on-ramp and off-ramp (i.e., VDS 1038 and VDS 1040), thereby the crash risk should also have been high theoretically because of the conflict vehicles, but the crash likelihoods in this station are small. The reason might be the bulk reduction of traffic flow in VDS 1028. In other words, the vehicles leaving from VDS 1038 may greatly more than the vehicles entering from VDS 1039. Then the vehicles entering from VDS 1040 make the traffic flow increase again, and the crash likelihoods in VDS 1030 also become larger on the basis of VDS 1028. Generally, the blocked upstream on-ramps will lead to the increasing of upstream risk, which will then affect the adjacent stations. Thus, the crash likelihoods of the adjacent stations may also increase. Consequently, the potential crash likelihoods are likely to occur at any areas of the whole WMD. That's why the crash likelihoods in VDS 1032 also increase. The crash likelihoods in VDS 1032 are higher than that of VDS 1030. This can be attributed to the reduced lanes from four to three, and the slowing down of vehicles leaving from VDS 1041 can also lead to more horizontal and vertical conflicts. After this, because of the increasing lanes in VDS 1042, the space for distributing traffic flow become comfortable, thus the crash likelihoods of VDS 1035 are lower than VDS 1032. After that, the lanes are reduced from four to three again in VDS 1036, and the conflicts of vehicles also increase. For this reason, the crash likelihoods in this station increase too. The crash risk of VDS 1036 reach another peak after the first peak occur in VDS 1026.

The above analysis is performed from spatial aspect, while the crash risks are also different in temporal aspect. The crash likelihoods in temporal are also unbalanced. Generally speaking, 16:30 to 17:30 is the peak hour with heavy traffic flow. Thus, the crash likelihoods during this period are also high, as shown in Fig. 8(a). All stations exhibit different degrees of crash risk during 16:30 to 17:30, especially during 16:30 to 17:00, the crash likelihoods are rather big. After 17:30, the crash likelihoods begin to decrease. The color in VDS 1028 and 1035 are approximately green after 17:30, which denotes the relatively safe state with low crash likelihoods in this period. Other stations still present some moderate crash risks but will maintain a downward trend. Finally, it is identified that the period of high crash risks is from 16:30 to 17:30, and the risks are relatively low after 17:30.

Fig. 8(b) demonstrates the new distribution of crash likelihoods under VSL scheme 1. Although some certain stations may present higher crash likelihood at certain moment after VSL scheme 1 is implemented. For example, the crash likelihoods of VDS 1026 from 18:05 to 18:10, the crash likelihoods of VDS 1028 at 16:40, and the crash likelihoods of VDS 1035 from 16:40 to 16:45 are all a little higher than that of without VSL. But the total and average crash likelihoods in the whole network of WMD have been largely reduced because of the implementation of VSL scheme 1. Up to now, the crash risk extents of peak hours in WMD have been identified, which further demonstrates the availability of Abdel-Aty's model in WMD.

### 6.2. Analysis of traffic congestion with and without VSL

Reasonable VSL control can also improve the traffic congestion of freeways. Because the key part of this paper is the evaluation of VSL to improve crash risk, the analysis of traffic congestion is secondary. So, only traffic flow and speed are considered in this study to evaluate the improvement of traffic congestion under VSL control schemes, and the congestion improvement should be the increasing of traffic flow passing by and the increasing of speed. The changes of speed and traffic flow passing of WMD before and after VSL control are shown in Fig. 9. It should be noted that all stations of WMD mainline are included, e.g., VDS 1018, VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS 1035, VDS 1036, VDS 1016, and VDS 1007. This is different on the analysis of crash likelihood (only the current stations like VDS 1026, VDS1028, VDS 1030, VDS 1032, VDS 1035 and VDS 1036 are included). Because in the calculation of crash likelihoods, only VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS1035 and VDS 1036 can be used as the current stations, while the traffic flow and speed don't need to follow this calculation, the other stations like VDS 1018, VDS 1016, and VDS 1007 can be also contained in the evaluation of congestion.

Fig. 9(a), (b) shows the traffic flow distributions before and after VSL scheme 1, and the traffic flow here denotes the passing vehicles. Traffic flow is expressed in different colors, i.e., red denotes large traffic flow, yellow denotes moderate traffic flow, and green represents small traffic flow. The colors in VDS 1018, VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS 1035, and VDS 1036 have been greatly deepened after the implement of VSL scheme 1, which illustrates that the vehicles passing from these stations are increasing. Hence, the traffic congestion may have been improved under VSL scheme 1, for the vehicles passing by can increase only in this case.

Fig. 9(c), (d) shows the speed distribution before and after VSL control. Green represents high speed, yellow denotes moderate speed, and red stands for low speed. Before VSL scheme 1 is performed, the speed of the most stations are close to 80 km/h except for VDS 1026 (see Fig. 9(c)). The speed of VDS 1026 is variable from 40 km/h to 60 km/h, and this station might be the most congested area. Especially, during 10:00 to 17:00, the speed is lower than 50 km/h, and this indicates the relatively bad traffic situation or the occurrence of serious congestion. After the implementation of VSL scheme 1, the speed of VDS 1026 are greatly enhanced and maintain at 70 km/h (see Fig. 9(d)), and this demonstrates that the congestion and bad traffic situation of VDS 1026 have been largely weakened under the impact of VSL scheme 1. But the speed of VDS 1018 from 16:00 to 18:00 is decreased, and the color is changed from green to red. This is mainly for the close location of VDS 1018 and 122 ST where VSL 1 is set (see Fig. 1). Because VSL scheme 1(the best scheme) present a changeable speed limits from 30 km/h to 80 km/h at peak hours, the speed of VDS 1018 is affected first by these variable speed limits at peak hours. This analysis suggests that VSL scheme 1 can also change the congestion distribution from spatial-temporal perspectives. Then the changes of speed in other stations are relatively small before and after VSL scheme 1 (see Fig. 9(c) and (d)). The above analysis interprets the validity of VSL scheme 1 in improving traffic congestion.

### 6.3. *t*-Test

A *t*-test method is used to further verify the results of the crash risk evaluation, i.e., whether the average crash likelihood in WMD under VSL scheme 1 (the best VSL control scheme) are significantly reduced. Because the real-time traffic flow under VSL and without VSL are mutually independent, the crash likelihoods based on traffic flow in these cases are also independent. Thereby the independent sample *t*-test is adopted to examine the statistical significance of the results. 95% confidence level is set. To satisfy the test conditions, what should be tested first is the normal distribution (i.e., One-Sample Kolmogorov-Smirnov Test in this study) and homogeneity of variance of the crash likelihoods under VSL scheme 1 and without VSL at different stations (i.e., station 1026, 1028, 1030, 1032, 1035, 1036). After this testing, the independent samples *t*-test can be performed. The normal distribution and homogeneity of variance of samples are confirmed by the statistical analysis. Then Table 9 illustrates the descriptive statistics of average crash likelihoods (i.e., the average value of every 5 min from 16:30 to 18:30) under VSL scheme 1 and without VSL, and then the results of the independent samples *t*-test shown as Table 10. Table 11 demonstrates the improvement extent of the average crash likelihood, average traffic flow passing and average speed from 16:30 to 18:30 under VSL scheme 1.

## 7. Result and discussion

The crash risks under VSL control schemes are contrasted with that of without VSL, which is conducted for determining the optimal VSL control scheme and identifying the crash risks of WMD from spatial-

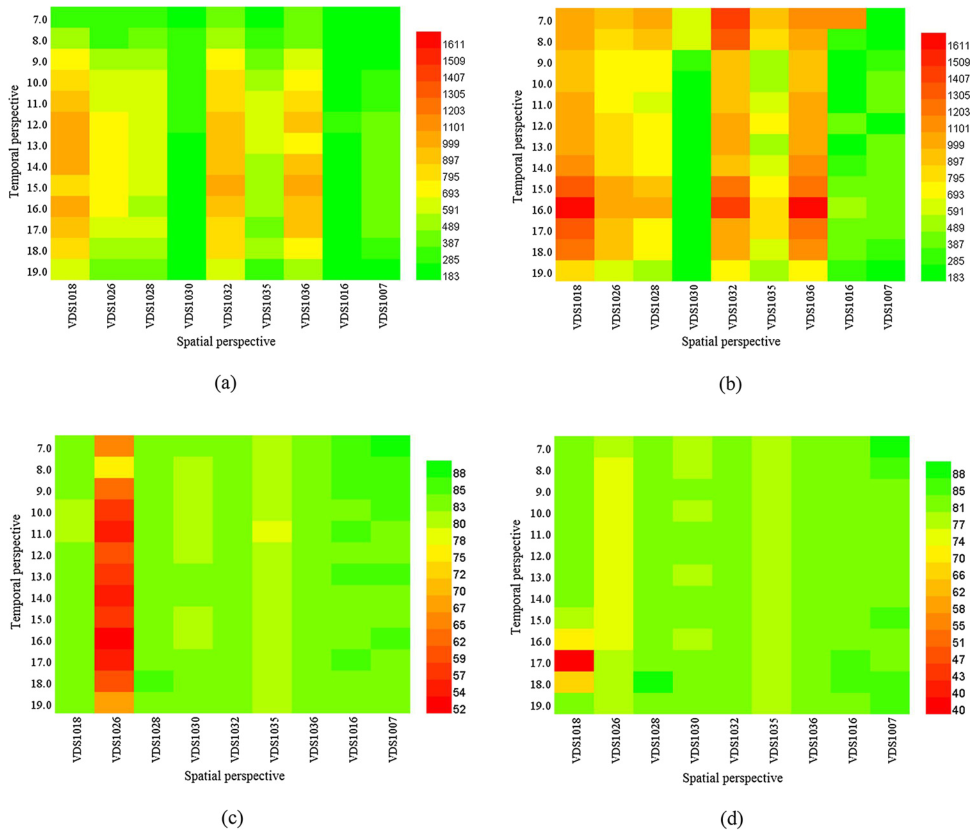


**Fig. 9.** Traffic congestion distributions under VSL scheme 1 and without VSL (a. traffic flow under without VSL b. traffic flow under VSL scheme 1; c. speed under without VSL; d. speed under VSL scheme 1).

**Table 9**
Descriptive statistics of crash likelihood under VSL scheme 1 and without VSL.

| Crash likelihood | Group | N | Mean | Std. deviation | Std. error mean |
|---|---|---|---|---|---|
| VDS 1026 | Without VSL | 24 | 4.8154 | 0.78352 | 0.15994 |
| | VSL scheme 1 | 24 | 3.6318 | 0.38355 | 0.16402 |
| VDS 1028 | Without VSL | 24 | 2.8198 | 0.65019 | 0.13272 |
| | VSL scheme 1 | 24 | 1.5010 | 0.94838 | 0.19359 |
| VDS 1030 | Without VSL | 24 | 3.8016 | 0.49758 | 0.10157 |
| | VSL scheme 1 | 24 | 1.8955 | 0.47824 | 0.09762 |
| VDS 1032 | Without VSL | 24 | 4.0247 | 0.74524 | 0.15212 |
| | VSL scheme 1 | 24 | 2.4026 | 0.68107 | 0.13902 |
| VDS 1035 | Without VSL | 24 | 3.4225 | 0.48584 | 0.09917 |
| | VSL scheme 1 | 24 | 2.1037 | 0.98640 | 0.20135 |
| VDS 1036 | Without VSL | 24 | 4.2469 | 0.50576 | 0.10324 |
| | VSL scheme 1 | 24 | 1.4652 | 0.33125 | 0.06762 |

temporal perspective. Furthermore, the traffic congestion is also evaluated.

As observed in Table 11, the average crash likelihood in WMD (including VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS 1035, and VDS 1036) are all associated with more than 20% reduction under the influence of VSL scheme 1. Among these reductions, the biggest occurs in station VDS 1036, then followed by VDS 1030, VDS 1028, VDS 1035, VDS 1032 and VDS 1026. This finding indicates that VSL scheme 1 may have a greater improvement on the moderate risk area than high risk area, i.e., the reduction in moderate risk stations like VDS 1030, VDS 1035, VDS 1032 (the reductions are 50.00%, 38.6% and 40.30% respectively) are larger than that of the highest risk area like VDS 1026 (the reduction is 24.69%). Overall, after the implement of VSL scheme 1, the risk degree of the most dangerous station is greatly reduced and is maintained at a safe level. Meanwhile, the relative safe stations become securer. Finally, the significances of VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS 1035, and VDS 1036 are all less than 0.05 (see Table 10), which indicates that all the reductions of crash likelihoods under VSL scheme 1 are statistically significant. These test results further verify the positive effect of VSL scheme 1 on improvements of the potential crash risk in WMD.

Furthermore, under the control of VSL scheme l, the congestions of WMD are also improved. This improvement can be recognized as the increasing of traffic flow and speed. The increasing of average traffic flow at VDS 1026, VDS 1028, VDS 1030, VDS 1032, VDS 1035, VDS 1036 shows little difference, and they raised by 28.22%, 28.82%, 17.03%, 26.14%, 27.27%, and 30.34% respectively. However, the speed raised by 21.05% at station 1026 (the most dangerous station), and the changes of other stations (i.e., VDS 1028, VDS 1030, VDS 1032, VDS 1035, and VDS 1036) are almost the same with only about 2% reduction that shows few differences with the condition of without VSL control. Hence this finding suggests that VSL scheme 1 may have a more significant improvement on the most congested station (i.e., station 1026) than other stations that are relatively uncongested.

## 8. Conclusion

This study evaluates the impact of VSL on improving the crash likelihood and congestion of WMD. A method based on spatial-temporal analysis is developed to guide the study. Spatial-temporal analysis results demonstrate that the average traffic flow of Monday (VSL scheme 3), Tuesday (VSL scheme 2), Wednesday (VSL scheme 1) and Thursday (VSL scheme 4) show high similarity. Thus, the average traffic flow of these days can be recognized as the traffic flow of the same day, i.e., VSL schemes 1, 2, 3 and 4 can somehow be the different VSL schemes of one day. Spatial-temporal analysis results on crash risk and congestion in WMD ascertained the best VSL control scheme, i.e., VSL scheme 1, and identified the crash risk and congestion degree of different stations at different time (i.e., VDS 1026 is both the most dangerous and

**Table 10**
Independent samples *t*-test.

| Station | Crash likelihood | T-test for equality of means | | | | |
|---|---|---|---|---|---|---|
| | | t | df | Sig. (2-tailed) | 95% Confidence | |
| | | | | | Lower | Upper |
| VDS 1026 | Equal variances assumed | 5.167 | 46.00 | 0.000 | 0.72251 | 1.64479 |
| | Equal variances not assumed | 5.167 | 45.97 | 0.000 | 0.72251 | 1.64480 |
| VDS 1028 | Equal variances assumed | 5.619 | 46.00 | 0.000 | 0.84635 | 1.79126 |
| | Equal variances not assumed | 5.619 | 40.71 | 0.000 | 0.84469 | 1.79292 |
| VDS 1030 | Equal variances assumed | 13.531 | 46.00 | 0.000 | 1.62255 | 2.18968 |
| | Equal variances not assumed | 13.531 | 45.93 | 0.000 | 1.62254 | 2.18969 |
| VDS 1032 | Equal variances assumed | 7.871 | 46.00 | 0.000 | 1.20732 | 2.03690 |
| | Equal variances not assumed | 7.871 | 45.63 | 0.000 | 1.20723 | 2.03700 |
| VDS 1035 | Equal variances assumed | 5.876 | 46.00 | 0.000 | 0.86699 | 1.77056 |
| | Equal variances not assumed | 5.876 | 33.54 | 0.000 | 0.86242 | 1.77514 |
| VDS 1036 | Equal variances assumed | 22.54 | 46.00 | 0.000 | 2.533 | 3.03000 |
| | Equal variances not assumed | 22.54 | 39.66 | 0.000 | 2.532 | 3.03100 |

**Table 11**
Improvement extent of average crash likelihood, average traffic flow passing and average speed under VSL scheme 1.

| Station | Average crash likelihood | Average traffic flow passing | Average speed |
|---|---|---|---|
| VDS 1026 | −24.69% | +28.22% | +21.05% |
| VDS 1028 | −46.81% | +28.82% | −2.01% |
| VDS 1030 | −50.00% | +17.03% | −2.06% |
| VDS 1032 | −40.30% | +26.14% | −2.96% |
| VDS 1035 | −38.60% | +27.27% | −2.11% |
| VDS 1036 | −65.41% | +30.34% | −2.27% |

Note: "+" represents increase; "-" represents decrease.

congested area; VDS 1028 is the safest station; 16:30 to 17:30 is the peak hours with the highest risk; 10:00 to 17:00 is the most congested time). Then an independent sample *t*-test is used to examine the significance of the result. An important finding is observed by *t*-test, i.e., the best VSL control scheme has a more significant effect on the moderate risk area than the high-risk area, and it also has a larger improvement on the most congested station than the relatively uncongested area.

The above results have the potential to help traffic managers incorporate crash risk prevention and congestion remission in the existing VSL control schemes and provide a detailed evaluation of the traffic condition of WMD. Meanwhile, the conclusion also provides a reference towards finding the best VSL control schemes by using VSL control as method to improve crash risk and congestion of freeways. Thereby this study has the double meaning in both engineering practice and theoretical research. However, before the results of this study are used in engineering practice and theoretical research, additional efforts are still needed. For example, the speed limits, VSL control locations, and control times are all fixed in the existing VSL control design in WMD, more VSL control schemes performed in other locations at other different periods need to be studied. Meanwhile the post-crash risk model based on VSL control is also important, which will reduce the actual loss of the crash accident. Finally, the transferability of the method from other freeways may also be tested. The authors suggest that future researches may focus on these issues.

## Acknowledgements

This research was supported by the National Natural Science Foundation of China (No. 51478110). The authors would like to thank the Open ITS for providing the primitive data, and also thank the editor and the anonymous reviewers for their constructive comments and valuable suggestions to improve the quality of the article.

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