MOUNTAIN-PLAINS CONSORTIUM

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RELIABILITY-BASED TRAFFIC SAFETY RISK ASSESSMENT OF TRAFFIC SYSTEM IN HAZARDOUS DRIVING CONDITIONS TO PROMOTE COMMUNITY RESILIENCE

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16. Abstract

For decades, work zone traffic safety under adverse weather conditions has been a serious concern for drivers and transportation agencies. Natural hazards often cause disruptions on roads and bridges and work zones during the retrofitting process. Existing studies on work zone traffic safety with statistical approaches are limited by the availability of data from historical crashes. To date, there is no comprehensive simulation framework to assess traffic safety on roads with work zones under adverse driving environments by considering both multi-vehicle and single-vehicle crashes. To fill this gap, this study presents an integrated framework to evaluate traffic safety in work zones under adverse driving conditions by considering specific work zone configuration, weather, and road surface conditions. A new risk index is introduced to assess the traffic safety risk of work zones by integrating the risks of multi-vehicle crashes and single-vehicle crashes. Traffic safety of a typical work zone under different weather conditions is studied to demonstrate the proposed framework. The impacts of the differential speed limits (DSL) and truck proportions on work zone traffic safety are also investigated. Results show that adverse weather may increase the crash risk in work zones. The effect of DSLs on work zone traffic safety is found to be insignificant, while truck ratio influences work zone safety in rainy and snowy weather by primarily affecting multi-vehicle crash risks.

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Reliability-based Traffic Safety Risk Assessment of Traffic System in Hazardous Driving conditions to Promote Community Resilience

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ABSTRACT[1]

For decades, work zone traffic safety under adverse weather conditions has been a serious concern for drivers and transportation agencies. Natural hazards often cause disruptions on roads and bridges and work zones during the retrofitting process. Existing studies on work zone traffic safety with statistical approaches are limited by the availability of data from historical crashes. To date, there is no comprehensive simulation framework to assess traffic safety on roads with work zones under adverse driving environments by considering both multi-vehicle and single-vehicle crashes. To fill this gap, this study presents an integrated framework to evaluate traffic safety in work zones under adverse driving conditions by considering specific work zone configuration, weather, and road surface conditions. A new risk index is introduced to assess the traffic safety risk of work zones by integrating the risks of multi-vehicle crashes and single-vehicle crashes. Traffic safety of a typical work zone under different weather conditions is studied to demonstrate the proposed framework. The impacts of the differential speed limits (DSL) and truck proportions on work zone traffic safety are also investigated. Results show that adverse weather may increase the crash risk in work zones. The effect of DSLs on work zone traffic safety is found to be insignificant, while truck ratio influences work zone safety in rainy and snowy weather by primarily affecting multi-vehicle crash risks.

[1] This report is based on the contents from the published journal paper: Hou, G. and Chen, S. (2020). "Study of work zone traffic safety under adverse driving conditions with a microscopic traffic simulation approach," *Accident Analysis and Prevention*, 145, 105698.

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1. INTRODUCTION AND LITERATURE REVIEW

1.1 Background

Highway work zones usually have a negative impact on traffic safety by reducing capacity and forcing drivers to perform multiple maneuvers (i.e., lane change, deceleration, and acceleration) in order to adapt to the modified road configurations (Bella 2005; Hou and Chen 2019). Many studies show that work zones cause a significant increase of crash risk. Hall and Lorenz (1989) examined work zone crashes over three years in New Mexico and found there was a 26% increase in vehicle crashes during construction or roadway maintenance. Results of Zhao and Garber's (2001) study showed that more fatal crashes occur in work zones than non-work zone locations. Khattak et al. (2002) reported that the total crash rate increases by 21.5% in the during-work zone period when compared with the pre-work zone period.

Adverse weather conditions (e.g., rain, snow, fog, strong crosswinds; wet, snowy, or icy pavement) is a major factor contributing to crashes. Nearly 1,235,000 weather-related crashes occur in the United States each year, leading to nearly 5,000 deaths and 418,000 injuries (FHWA 2005). Numerous studies investigated the impact of different risk factors on work zone crashes and the adverse weather condition was identified as a significant factor (Qi et al. 2005; Li and Bai 2009). Counterintuitively, adverse weather was found to reduce the work zone crash rate and injury severity in several studies based on historical data (Zhao and Garber 2001; Harb et al. 2008). There are two main possible explanations for such findings: one is that drivers are generally more vigilant during inclement weather and the other one is that most construction activities are conducted under relatively good weather conditions. In addition to the factors identified above, there are other critical factors that must be considered. For example, during adverse weather, reduced vehicle speed and decreased pavement friction coefficients are found to have negative and positive impacts on vehicle crashes, respectively (Abdelmohsen and El-Rayes 2018; Chen and Chen 2010). Because these causation studies were based on statistical analyses of limited historical crash data on a case-by-case basis, more general impacts of adverse weather on work zone crashes have not been well understood.

Another controversial issue regarding traffic safety is differential speed limits (DSL). Some states set DSLs for passenger cars and large trucks. The effect of DSLs for cars and trucks on traffic safety has been inconclusive in previous studies (Duncan et al. 1998; Idaho Transportation Department 2000; Garber et al. 2006; Dixon et al. 2012). Some studies show that a DSL produces increased potential conflicts between passenger cars and large trucks, which may lead to a possible increase in crashes, i.e., primarily rear-end and lane change collisions (Duncan et al. 1998). However, some other studies found that a DSL improves traffic safety performance by lowering crash risks (Dixon et al. 2012) or does not cause an increase in vehicle crashes (Idaho Transportation Department 2000; Garber et al. 2006). On highways with DSLs, when experiencing geometric changes such as work zones, trucks and cars normally obey the DSL in normal areas but follow the same reduced speed limit in work zone areas. Despite the popularity of DSLs, there have been very few research studies examining the crash risk of work zone traffic where a DSL is applied.

A considerable amount of research has been performed to identify factors related to vehicle crashes and predict the likelihood of crashes on highway facilities with statistical models (Mannering and Bhat 2014). However, it is well known that the performance of statistical models strongly relies on the quality and quantity of collected crash data. For example, Lord and Mannering (2010) summarized some issues associated with crash frequency data: first, crash data are often characterized by a small number of observations because of the high costs associated with the data collection process; second, many near-crashes and minor crashes are not recorded in traditional crash databases; third, some important factors affecting crashes are not collected (i.e., vehicle speed, driver braking, and maneuvering responses). These issues may lead to estimation errors and incorrect conclusions relating to the factors that determine the frequency of crashes. Compared with statistical modeling approaches, simulation-based approaches have several advantages in terms of investigating work zone crashes. First, they are much less dependent on the availability of actual crash data than data-driven approaches. In fact, crash data under some adverse weather conditions can be very scarce, and statistical modeling would therefore be very hard to carry out. Second, a simulation-based approach can model the whole process of a crash occurrence and provide some scientific insights regarding how a crash occurs under a specific condition. Therefore, a simulation-based approach is a viable method for investigating work zone crashes, especially under adverse weather conditions when the actual field data are usually scarce.

In the present study, a holistic framework is developed for studying traffic safety in work zones under adverse weather conditions; based on this framework, a safety performance index of work zone is further introduced. First, in the proposed framework, traffic flow under different weather conditions is simulated with the cellular automaton (CA) model. Second, with time-dependent vehicle information from the traffic flow simulation, the probabilities of multi-vehicle crashes (MVC) and single-vehicle crashes (SVC) of the traffic flow are predicted. Third, a risk index is introduced to evaluate work zone traffic safety under adverse weather conditions by considering both MVCs and SVCs. Following the proposed framework, traffic safety of a typical work zone under different weather conditions will be studied. Finally, the effect of DSLs and truck proportion on work zone traffic safety will also be investigated.

1.2 Literature Review

Adverse weather conditions such as rain and snow have been found to significantly affect traffic performance in several ways. According to the Highway Capacity Manual 2000 (HCM 2000), rain could reduce freeway capacity by 0% to 15%, depending on the rainfall intensity. Capacity reductions caused by light and heavy snow are around 5% to 10% and 25% to 30%, respectively. Maze et al. (2006) found that freeway capacity reduction caused by rain and snow were about 2% to 14% and 4% to 22%, respectively. According to Agarwal et al. (2005), heavy rain and snow could reduce freeway speed by 4% to 7% and 11% to 15%, respectively. Moreover, rain and snow can reduce the friction between tires and pavement, which further influences vehicle performance and driver behavior. For example, a decreased pavement friction coefficient leads to decreased deceleration capability of vehicles; in which case, drivers tend to drive more cautiously on slippery roads with decreased acceleration and deceleration rates in order to avoid skidding (Asamer et al. 2011; Zhao et al. 2012).

Some studies have been conducted to investigate the effect of adverse weather on traffic flow characteristics with simulation techniques. For example, Zhao et al. (2012) modeled the impact of inclement weather on freeway speed with the CA-based traffic simulation model TRANSIMS, which was calibrated with collected vehicle data under normal and snowy weather conditions. They found that driving under inclement weather conditions is characterized by higher frequency and lower magnitude of acceleration and deceleration, compared with normal weather conditions. Rakha et al. (2012) investigated the influence of inclement weather on traffic flow with the traffic flow simulation software INTEGRATION. Results showed that rain and snow result in different levels of speed reduction. Chen et al. (2019) studied the effect of weather on traffic flow characteristics by combining driving simulator experiments and traffic simulation. In the study, driver simulator experiments were conducted to collect driving behavior data during different weather conditions, which were further incorporated in the microscopic traffic simulation program VISSIM.

In recent years, there has been increased interest in the study of work zone traffic flow with CA models. Meng and Weng (2011) introduced a randomization probability function, which is expressed as a function of traffic flow and work zone configuration, to replace randomization probability parameters in traditional CA models, and calibrated and validated their model microscopically and macroscopically with real work zone data. Fei et al. (2016) investigated highway work zone traffic with a meticulous two-lane CA model.

In order to realistically reproduce the work zone traffic dynamics, different forwarding rules and lane-changing rules were applied to different areas: normal area, merging area, and work zone area. Hou and Chen (2019) proposed an improved CA model to simulate work zone traffic, in which realistic driving behaviors can be captured by eliminating unrealistic deceleration behaviors commonly found in traditional CA models.

MVCs in one-lane and two-lane traffic flow have been extensively studied with CA-based traffic simulation models. Instead of directly simulating traffic crashes, the occurrence of dangerous situations (DS), which could lead to collisions by unsafe driving behaviors, were often studied. Moussa (2003) introduced conditions for the occurrence of DS caused by stopped cars and abrupt deceleration for one-lane traffic flow. In order to study traffic crashes in two-lane traffic, Moussa (2005) further introduced conditions for the occurrence of DS caused by unexpected lane-changing vehicles. It was found that the probability of crashes caused by lane change is well related to the lane-changing frequency of two successive cars that switch lanes simultaneously. Mhirech and Alaoui-Ismaili (2015) studied the effect of traffic lights on traffic crashes and found that the increase of cycle time leads to a decrease of the crash probability. Pang et. al. (2015) studied the impact of low-visibility weather on rear-end crashes on a three-lane freeway. The results showed that measures such as incoming flow control and installing variable speed limit signs can effectively reduce crashes. Marzoug et al. (2017) investigated crashes at the entrance of a bottleneck where two lanes join with a CA model. Non-cooperative drivers were found to increase the crash risk in moderate and heavy traffic.

In addition, it is known that vehicles are very vulnerable to SVCs (e.g., rollover or sideslip crashes) under hazardous driving conditions, such as strong crosswinds and icy or snowy road surfaces. There have been many studies on SVCs occurring on roads and long-span bridges with deterministic or probabilistic vehicle crash models (Chen and Cai 2004; Snaebjornsson et al. 2007; Chen and Chen 2011; Zhou and Chen 2015; Kim et al. 2016; Wang et al. 2016; Hou et al. 2019a). Chen and Cai (2004) proposed a framework of vehicle crash simulation on long-span bridges by considering wind-bridge-vehicle interactions. Zhou and Chen (2015) further explored traffic safety on bridges by considering full-coupling effects among all vehicles in the traffic, as well as bridge and wind in their bridge-traffic interaction analysis model. In the study by Wang et al. (2016), the safety of vehicles moving on the ground under a sudden crosswind was evaluated with a nonlinear safety assessment model, in which wind loads and mass moments of a vehicle vary with its angular displacements. Based on previous deterministic vehicle crash models, Snaebjornsson et al. (2007) and Chen and Chen (2011) developed probabilistic crash models in which uncertainties of critical variables, such as vehicle parameters, vehicle speed, wind velocity, road surface coefficient of friction, and superelevation, were considered. Different from most existing studies focusing on a single vehicle moving at a constant speed, Hou et al. (2019a) proposed a methodology investigating the traffic safety of every moving vehicle of the traffic flow. With this tool, the overall SVC risk of the realistic stochastic traffic passing through a highway system can be evaluated.

According to our literature review, very few studies have been conducted on work zone crashes based on simulation, and even fewer have focused on both MVCs and SVCs. For example, Chen et al. (2011) developed a multi-scale approach to evaluate the traffic safety of large trucks on intact mountainous interstate highways, in which MVCs and SVCs were studied with two separate simulation-based models. Pang and Ren (2017) investigated the effect of rainy weather on freeway crashes with a CA model. Rear-end and sideslip crashes under different rainfall intensities were analyzed in this study. However, their sideslip crash model can only simulate crashes induced by the transverse slope, but not other causes. Despite the progress, as summarized above, most of the aforementioned studies focused on either MVCs only, SVCs only, or both MVCs and SVCs on normal driving environments and intact roads. There is no simulation-based model that can be used to study both MVCs and SVCs when there are work zones and adverse driving environments.

1.3 Organization of This Report

This study aims to evaluate traffic safety in work zones under adverse driving conditions by considering work zone configurations, weather conditions, and road surface conditions. An integrated simulation framework, including traffic simulation, MVC simulation, SVC simulation, and safety risk assessment, is proposed. Furthermore, as the unique contribution is based on the proposed simulation framework, the overall risk of both MVCs and SVCs can be assessed with an integrated risk index, which will be introduced in the following.

The novel contributions of this study include (1) proposing a simulation framework which can evaluate work zone traffic crash risk under adverse weather conditions, and (2) introducing an integrated risk index that assesses the overall risk of different types of vehicle crashes.

The report is composed of four chapters: Chapter 1 introduces pertinent background information and literature review results related to the present study. In Chapter 2, the modeling process of traffic safety assessment methodology is introduced. In Chapter 3, numerical demonstration of the new modeling technique is conducted and the results are discussed. Chapter 4 summarizes the findings from the report.

2. SIMULATION-BASED FRAMEWORK

An integrated framework is developed to assess the traffic safety of work zones under adverse weather conditions focusing on the risks of both MVCs and SVCs. As shown in Figure 2.1, the proposed framework includes four main parts: first, work zone traffic is simulated with a CA model by considering work zone configuration, weather conditions, vehicle proportion, vehicle density, and speed limit; second, multiple-vehicle safety of the simulated work zone traffic is assessed in terms of crash probabilities by considering two types of rear-end collisions; third, single-vehicle safety performance is assessed with an advanced framework based on the time-dependent vehicle information from the traffic simulation; finally, an overall work zone traffic safety assessment is conducted by considering both MVCs and SVCs. The details of each part of the framework is introduced as follows.

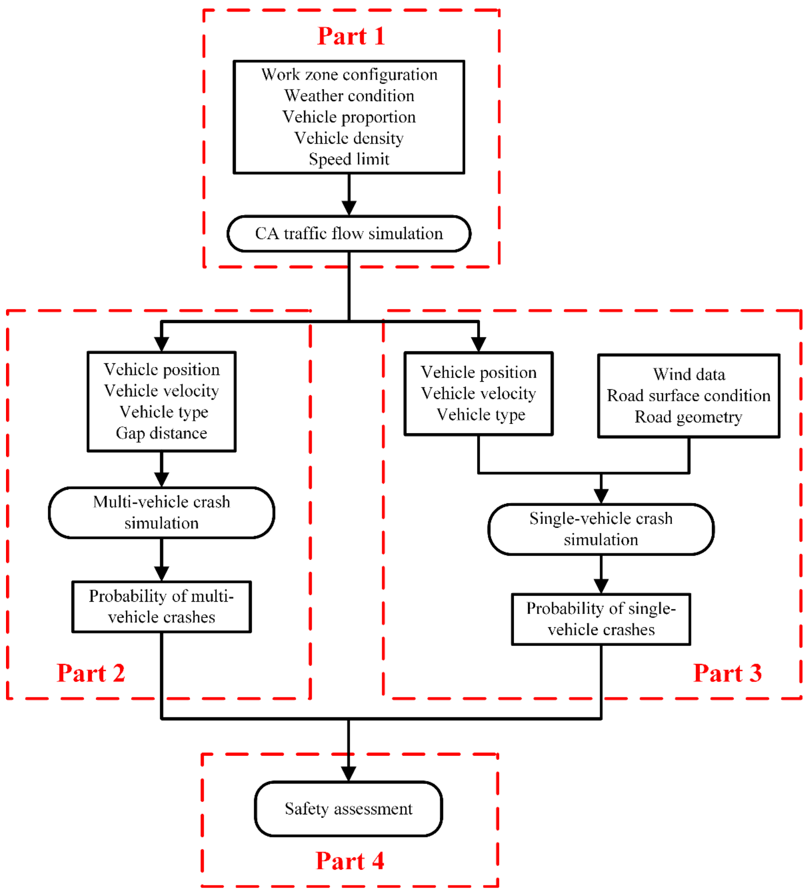


Figure 2.1 Flowchart of work zone crashes simulation

2.1 Simulation of Work Zone Traffic under Different Weather Conditions

A typical work zone includes an advance warning area, transition area, activity area, and termination area. For simplicity, the transition, activity, and termination areas are called the work zone area altogether in the following study. A warning sign is placed at the beginning of the advance warning area to inform road users about the incoming work zone and the reduced speed limit. Figure 2.2 shows the configuration of a typical road section with a simplified work zone.

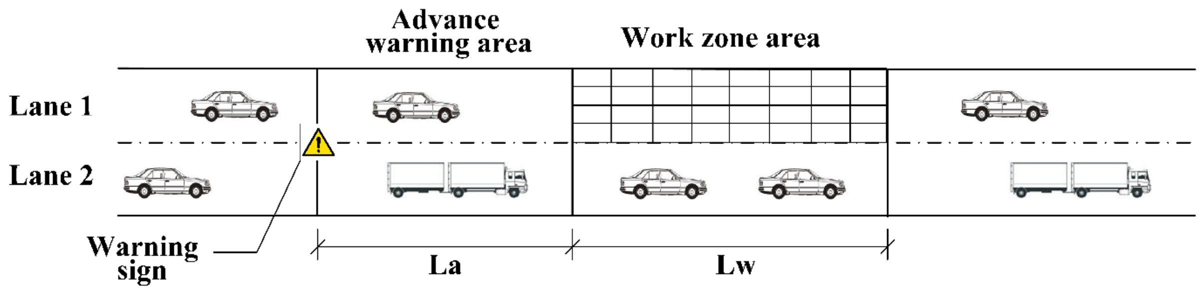


Figure 2.2 Configuration of a typical work zone

The cellular automaton (CA) technique is one of the most widely used microscopic traffic simulation methods. Despite its simplicity, the CA technique can simulate the traffic flow realistically and efficiently (Hou et al. 2017, 2019b). In this study, a CA model developed previously by the authors is used to simulate the work zone traffic. In the model, the lanes are discretized into many identical cells. Each cell is either empty or occupied by a vehicle at a time. At each time step, the position and velocity of each vehicle are updated following the forwarding rules and lane-changing rules. The forwarding rules include four consecutive steps, i.e., acceleration, deceleration, random brake, and movement, which are performed in parallel for all vehicles. Because of the reduced speed limit in the advance warning area and work zone area, the maximum velocity of vehicles in these areas is smaller than that in the normal area. Moreover, in the advance warning area, vehicles in the blocked lane (lane 1) will try to change to the unblocked lane (lane 2) as soon as possible, and vehicles in lane 2 will not change lanes. Therefore, the lane-changing probability for vehicles in lane 2 in the advance warning area is set as 0. Otherwise, the lane-changing probability is set as 1 throughout this paper. More details about the CA model can be found in Hou et al. (2019b). Previous research shows that adverse weather such as rain and snow cause a reduction of vehicle speed, acceleration, and deceleration rates (Asamer et al. 2011; Zhao et al. 2012). Therefore, the impact of adverse weather on traffic flow is incorporated in the traffic simulation by using reduced maximum vehicle speed, acceleration, and deceleration rates. Detailed values of these parameters under different weather conditions will be given and discussed in the following demonstrative study.

2.2 Multi-vehicle Crash (MVC) Simulation

Previous studies about simulation-based multi-vehicle crashes (MVC) mainly focused on the occurrence of a dangerous situation (DS), which could lead to rear-end collisions between vehicles (Yang and Ma 2002; Jiang et al. 2003). If DS's exist, a collision is deemed to occur at the next time step with a probability p', which refers to the careless driver probability (Moussa 2003). In MVC simulation models (Moussa 2003, 2004; Yang et al. 2004), some drivers were assumed to be careless in the traffic flow. The main characteristic of a careless driver was that when the car ahead is moving, he or she expects it to move again at the next time step, and therefore his/her braking maneuver was made only after a delayed reaction time.

In this study, two types of crashes are considered. Type I crashes are rear-end collisions mainly caused by abrupt deceleration of the leading vehicle. The conditions for the occurrence of a DS corresponding to Type I crashes can be expressed by Eqns. (1) and (2). In such a DS, the leading vehicle decelerates abruptly, and the covered distance during the delayed reaction time τ of the following vehicle is more than the distance to the leading vehicle at the next time step.

$$\tau v_i^t > gap_i^t + v_{i+1}^{t+1} \quad (1)$$

$$v_{i+1}^t - v_{i+1}^{t+1} \geq v_d \quad (2)$$

where τ is the reaction time and equals 1 s in this study; v_d is the deceleration limit of the leading vehicle, $v_d = \mu g$; μ is the pavement friction coefficient; g is the gravitational acceleration.

Type II crashes are rear-end collisions caused by simultaneous lane changes of two successive vehicles (Moussa 2005). The first condition of a DS corresponding to Type II crashes is that two successive vehicles change lanes at the same time and to the same target lane. The second condition can also be expressed by Eqn. (1). In such a DS, the driver of the leading vehicle does not pay sufficient attention to the vehicle behind before changing lanes. This could lead to a rear-end collision on the target lane.

Based on the time-dependent vehicle information (i.e., vehicle position, vehicle velocity, vehicle type, and gap distance) from the traffic flow simulation introduced in the previous section, a DS can be identified by checking whether the above-mentioned conditions are satisfied at each time step. The probability of a DS per vehicle and per time step is defined as follows:

$$P_{ds} = \frac{1}{N}\frac{1}{T}\sum_{t=1}^{T}\sum_{n=1}^{N} DS(t) \tag{3}$$

where N is the total number of vehicles; T is the simulation time; $DS(t) = 1$ if a DS occurs at a time instant t, otherwise $DS(t) = 0$.

The probability of an MVC, namely, the probability per vehicle and per time step for a crash, is proportional to the careless driver probability. However, because the careless driver probability is usually unknown, the DS probability P_{ds} is treated as a surrogate of the probability of an MVC in this study, which has been adopted in some previous studies (Li et al. 2014; Mhirech and Alaoui-Ismaili 2015).

2.3 Single-vehicle Crash (SVC) Simulation

Vehicles are very vulnerable to SVCs under adverse weather conditions (i.e., strong wind, wet or snowy road surface). A framework previously developed by the authors (Hou et al. 2019a) will be used to evaluate the single-vehicle traffic safety in work zones under adverse weather conditions. In order to provide some essential background information, the framework is briefly introduced as follows.

An SVC simulation model (Chen and Chen 2010) is the core part of the framework. In the model, a vehicle is modeled with three rigid bodies, one representing the sprung mass and the other two for the unsprung masses of the front and rear axles. The sprung mass rotates about the roll axis in a manner representing the kinematic properties of the front and rear suspensions. The unsprung masses can also rotate to consider the effect of the vertical compliance of the tires. Five differential equations of motion are built to describe the balance of the lateral force and the yaw moment of the entire vehicle, and the roll motion of the sprung and unsprung masses. The detailed equations of motion and related parameters can be found in the Ref. (Chen and Chen 2010). The model can simulate rollover and sideslip crashes of individual vehicles under complex geometric and other environmental conditions (e.g., crosswinds, road surface). The “critical sustained time” (CST) is used when assessing crashes under hazardous conditions. CST refers to the minimum time required to sustain the specific combination of the adverse environments and driving conditions to enable a crash to occur. In this study, a crash is defined as the situation when the CST of a vehicle is less than 1.0 s, which is also the assumed reaction time of drivers. The median reaction time reported in previous experimental studies ranged from 0.9 to 1.14 s (Johansson and Rumar 1971; Wortman et al. 1983; Chang et al. 1985; Sivak et al. 1982). Therefore, a reaction time of 1.0 s is used in this study in order to consider more general cases.

With the time-variant information of any individual vehicle from the traffic flow simulation described in the previous section, crash simulation of that vehicle is performed with the SVC model. The crash occurrence of each vehicle in the simulated traffic flow will be checked at every minute to assess the overall vehicle safety performance. Vulnerable vehicle ratio at every minute is defined as the ratio of the number of vehicles that experience rollover or sideslip crashes to the total number of vehicles in the traffic flow. To consider the stochastic nature of traffic flow, the same experiments are repeated over time continuously by evaluating the passing vehicles through the same observation window. Based on the basic statistical analyses of the results from the repeated experiments, the probability of SVC P^s can be expressed as the median value of the vulnerable vehicle ratios throughout the entire simulation time, as shown in Eqn. (4).

$$P^s = M\{R_1, R_2, \cdots, R_T\} \quad (4)$$

where P^s is the SVC probability; $R_i = n_i/N_i$, R_i is the ratio of the vulnerable vehicles at the i^{th} minute, n_i is the number of vehicles that experience rollover or sideslip crashes at the i^{th} minute, and N_i is the total number of vehicles in the traffic at the i^{th} minute; T is the total number of repeated experiments; and M is the median function.

2.4 Work Zone Safety Assessment

Based on the MVC and SVC assessments, probabilities of MVC and SVC occurrence under different adverse weather conditions can be obtained. However, because MVCs and SVCs often occur under different conditions, it is impossible to evaluate work zone safety by simply summing up probabilities of MVCs and SVCs. For example, MVCs are mainly associated with traffic congestion, adverse road surface conditions, and careless drivers, while SVCs are often caused by strong crosswinds as well as other weather and road surface factors (Moussa 2003; Harb et al. 2008; Chen and Chen 2010). Therefore, it is necessary to introduce a new index to assess work zone safety under different adverse conditions by simultaneously considering both MVCs and SVCs.

First, the overall crash vulnerability is defined as the area between the crash probability curve and the traffic density axis for MVCs, or the volume between the crash probability surface and the traffic density-wind speed plane for SVCs. Therefore, the overall vulnerability of MVCs and SVCs can be expressed by Eqns. (5) and (6).

$$V_u^m = \int P^m(\rho) d\rho \quad (5)$$

$$V_u^s = \iint P^s(\rho, u) d\rho du \quad (6)$$

where V_u^m and V_u^s are the overall vulnerability of MVC and SVC, respectively; P^m and P^s are the probability functions of MVC and SVC, respectively; ρ is the traffic density; u is the wind speed.

Second, the individual vulnerability index VI of MVC and SVC under a particular adverse condition is introduced by comparing the overall vulnerability under the adverse condition with that under the normal condition, which can be expressed by Eqn. (7). In this equation, a larger vulnerability index means higher MVC or SVC risk.

$$VI = \frac{V_u'}{V_u} \quad (7)$$

where V_u and V_u' are the MVC or SVC vulnerability under normal and adverse conditions, respectively.

Finally, an integrated risk index RI is proposed to evaluate the safety of a work zone under an adverse condition by considering the crash risk of both MVCs and SVCs, as shown in Eqn. (8). VI^m and VI^s represent individual vulnerability indexes of MVCs and SVCs, respectively. θ is the weight parameter to define the contributions from different types of crashes, which can be decided based on site-specific data or preference by the stakeholders based on the specific circumstances and priorities.

$$RI = \theta VI^m + (1 - \theta) VI^s \tag{8}$$

3. DEMONSTRATIVE STUDY

Without losing generality, the proposed framework will be demonstrated on a virtual highway segment with a total length of 2,000 m, as shown in Figure 2.2. The length of the advance warning area and the work zone area are assumed to be $L_a = 300\ m$ and $L_w = 400\ m$, respectively. In the CA model, a small cell length of 0.5 m is adopted to provide high simulation accuracy, and the simulation time step is 1 s (Hou et al. 2017). By balancing simulation efficiency and accuracy, all the vehicles in traffic are categorized into two types primarily from a traffic safety perspective: cars and trucks, and the ratio of trucks is assumed to be $R_t = 0.1$. Table 3.1 gives the values of other parameters such as acceleration rate, deceleration rate, and maximum velocity in the CA model under different weather conditions. Values of acceleration and deceleration rates of cars and trucks during clear weather recommended by Hou et al. (2017) are adopted in this study, as shown in Table 3.1. According to the GPS-equipped vehicle trajectory, including speed and longitudinal acceleration collected by Zhao et al. (2012) during snowy weather conditions, both acceleration and deceleration rates of cars are set as 1 m/s^2. Because trucks usually have lower acceleration and deceleration capability than cars (Li et al. 2016; Fei et al. 2016), a smaller acceleration and deceleration rate of 0.5 m/s^2 during snowy weather is assumed based on the existing literature.

As discussed previously, adverse weather conditions usually lead to decreased acceleration and deceleration rates of vehicles. Due to the lack of related data, acceleration and deceleration rates of vehicles under rainy weather conditions are assumed to be lower than those under clear weather conditions but higher than those under snowy weather conditions, as shown in Table 3.1. According to FHWA (2005), free-flow speed can be reduced by 6% to 17% in heavy rain and 5% to 64% in heavy snow. It is assumed that the reductions of free-flow speed due to rain and snow are 10% and 30%, respectively. Meanwhile, a reduction of free-flow speed of 10 mph (4.5 m/s) in the work zone area, as compared with the normal area, is applied in this study. According to Walus and Olszewski (2011), pavement friction coefficients under clear, rainy, and snowy weather conditions are set as 0.7, 0.4 and 0.2, respectively. In the SVC assessment, detailed parameters in dynamic models of cars and trucks can be found in the References (Hou et al. 2019a). These parameter values listed above will be used throughout this study unless otherwise specified.

Table 3.1 Parameter values of CA model under different weather conditions

Weather condition	Maximum velocity (m/s)				Acceleration (m/s^2)		Deceleration (m/s^2)	
	Normal area		Work zone area					
	Car	Truck	Car	Truck	Car	Truck	Car	Truck
Clear	33.5	33.5	29	29	2	1.5	2	1.5
Rainy	30	30	25.5	25.5	1.5	1.0	1.5	1.0
Snowy	23.5	23.5	19	19	1.0	0.5	1.0	0.5

3.1 Work Zone Traffic Safety under Different Weather Conditions

Previous studies with data-driven crash analysis show that work zone crashes are less likely to occur during adverse weather than clear weather (Zhao and Garber 2001; Harb et al. 2008). Because of the limitation of historical crash data, underlying reasons of such observations were not yet clear. In this section, work zone traffic safety under different weather conditions (i.e., clear, rainy, and snowy) are investigated. The proposed framework introduced in the previous section is adopted to calculate the probabilities of different types of crashes and crash-related indexes such as vulnerability indicator and risk index.

3.1.1 Flow-density Relationship

First, To gain a better understanding of the effect of weather conditions on work zone mobility, flow-density diagrams under different weather conditions are compared in Figure 3.1. The variations of flow rate share similar trends for three weather conditions. First, the flow rate increases linearly with traffic density in light traffic and reaches a peak. Then, a plateau is formed when the traffic is relatively heavy. Finally, the flow rate decreases as the traffic density increases. According to Hou et al. (2019b), the peak and plateau on the flow-density diagram are two typical characteristics of work zone traffic with uniform speed limit (USL). In addition, it is found that the traffic capacities under clear, rainy, and snowy conditions are 2,093, 1,912, and 1,673 veh/h, respectively. As compared with clear weather, the capacity reductions due to rain and snow are 8.6% and 20.1%, respectively. The results are consistent with the Highway Capacity Manual 2000 (HCM 2000) and the findings reported by Maze et al. (2006).

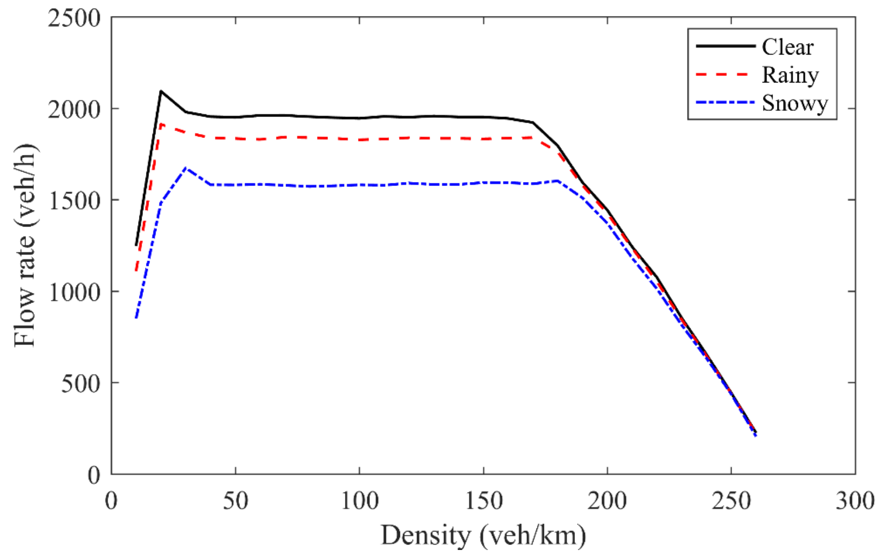


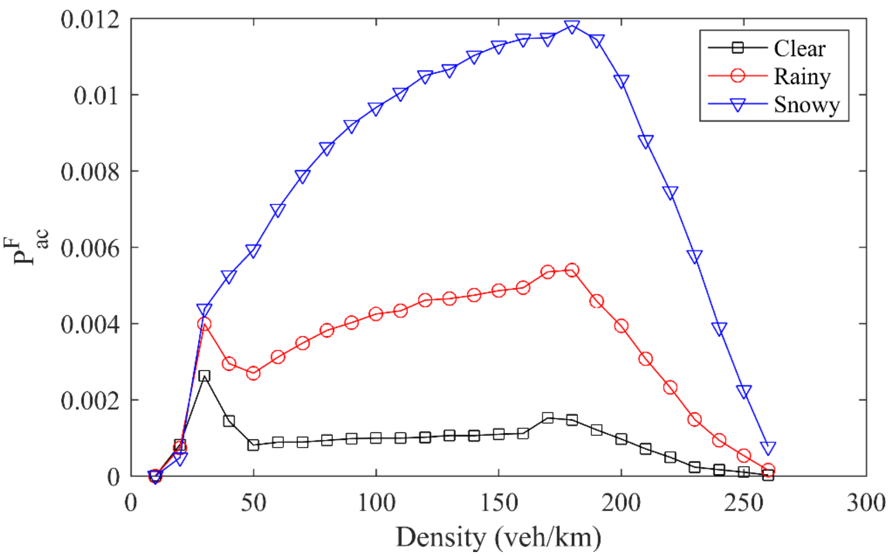
Figure 3.1 Flow-density diagrams under different weather conditions

3.1.2 Multi-vehicle Crashes

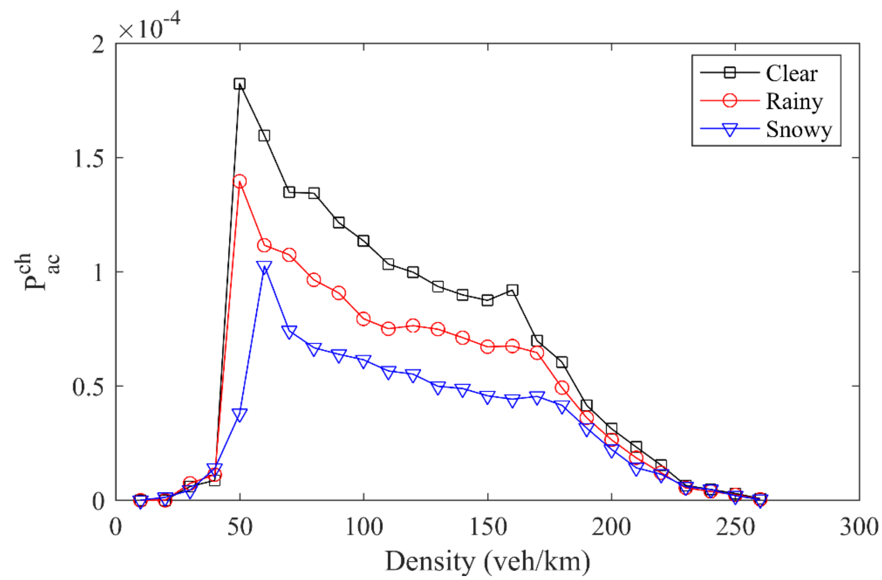
Second, multi-vehicle crashes (MVC) under different weather conditions are studied. Figures 3.2(a) and (b) show the probability of Type I and Type II crashes, P_{ac}^{F} and P_{ac}^{ch}, under different weather conditions, respectively. As shown in Figure 3.2(a), Type I crashes occur even at low traffic densities because of the increased speed variation among vehicles induced by the work zone. However, there are different patterns of the crash probability under different weather conditions. During clear weather, the probability of Type I crashes P_{ac}^{F} first increases as traffic density increases, reaches its peak value at $\rho = 180$ veh/km, and then decreases. However, under rainy and snowy weather conditions, there are two peaks: at $\rho = 30$ veh/km and around $\rho = 170$ veh/km, respectively. It is found that Type I crash probability P_{ac}^{F} during clear weather is much smaller than that during rainy and snowy weather.

Figure 3.2(b) shows that the probability of Type II crashes P_{ac}^{ch} is much smaller than that of Type I crashes P_{ac}^{F}. For example, the maximum value of P_{ac}^{ch} during rainy weather is 3% of that of P_{ac}^{F}. Type II crash probabilities under three different weather conditions show similar variation patterns as Type I crashes: P_{ac}^{ch} increases with the increase of traffic density, reaches the maximum value at around $\rho = 50$ veh/km, and then decreases with the further increase of density. By comparing Figure 3.2(b) and

Figure 3.3 about the lane-changing frequency under different weather conditions, it is found that P_{ac}^{ch} is closely related to the lane-changing frequency. Moreover, it is observed in Figure 3.2(b) that P_{ac}^{ch} during clear weather is larger than that during rainy and snowy weather. This is possibly because higher speed and acceleration/deceleration rate in clear weather cause more lane change maneuvers, which further lead to higher probability of Type II crashes.



(a) Type I crash



(b) Type II crash

Figure 3.2 MVC probability under different weather conditions

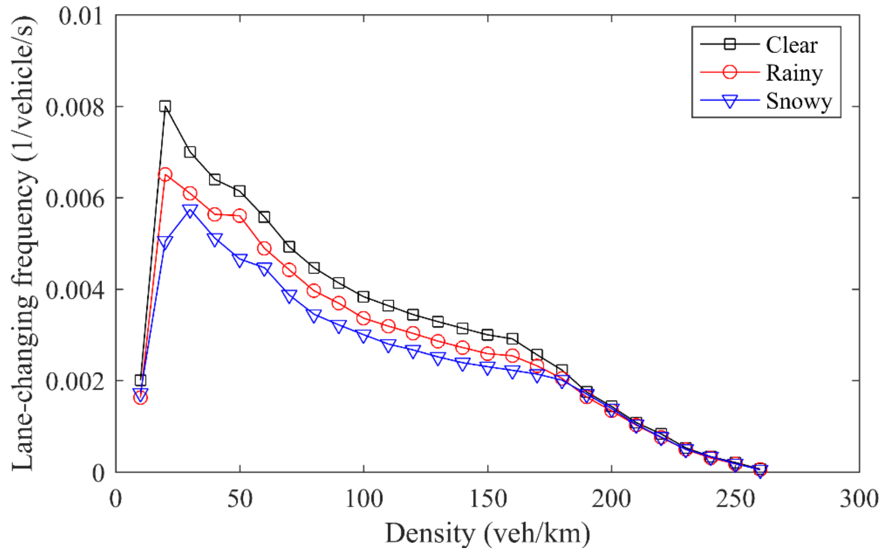
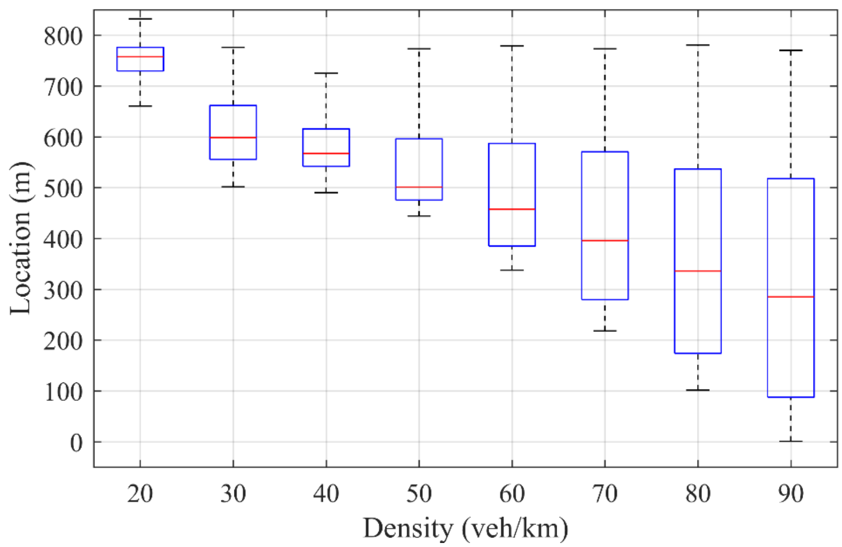


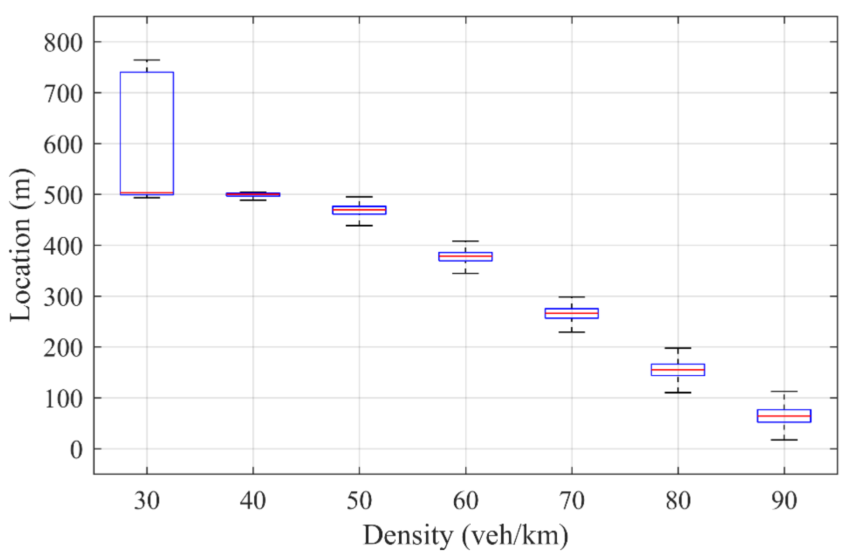
Figure 3.3 Lane-changing frequency under different weather conditions

Figures 3.4(a) and (b) list the box plots of locations of where Type I and II crashes may occur under rainy weather, respectively. The longitudinal location of some critical points of the studied highway work zone, including the start of the studied road segment, the warning sign, the start of the work zone area, the end of the work zone area, and the end of the studied road segment, are $x = 0$, 500 m, 800 m, 1200 m, and 2000 m, respectively. It is found that both Type I and II crashes mainly occur in the upstream of the work zone area, and the median value of the vertical axis values (crash location) shown in Figure 3.4 decreases with the increase of traffic density. This is because traffic congestion forms in the upstream of the work zone and moves backwards as the traffic density increases. Crashes induced by abrupt deceleration and lane change mainly occur in the area where the traffic congestion forms. The difference is that Type I crashes happen throughout the whole congested area while Type II crashes mainly happen in the upstream of the congested area. Because of this, there are some different distribution patterns for Type I and II crashes.

For Type I crashes, as shown in Figure 3.4(a), as traffic density increases, the interquartile range generally becomes larger and the whiskers become wider, indicating increased variability of the crash location. This is because traffic congestion becomes worse by forming longer platoons as traffic density increases. Regarding Type II crashes, the crash location varies very little except for the case when the density is $\rho = 30\ \text{veh/km}$. It can be found that the variation of the crash location is relatively large for Type I and II when the density $\rho \leq 30\ \text{veh/km}$. This is because traffic congestion under these situations is very mild and traffic speed is relatively high, and therefore traffic crashes could happen with higher uncertainty. It can also be seen in Figure 3.4(b) that when the density $\rho \leq 50\ \text{veh/km}$, Type II crashes occur mainly near the location of $x = 500$ m, where the advance warning sign is placed. This is because lane change maneuvers are mostly performed near the warning sign at relatively low densities.



(a) Type I crash



(b) Type II crash

Figure 3.4 Box plot of MVC location under rainy weather

Figure 3.5 shows the composition of different vehicle types of those involved in MVCs under snowy weather. As shown in Figure 3.5, due to the high ratio (90%) of cars in traffic, car-involved crashes account for high percentages of both Type I and Type II crashes. Because of higher acceleration and deceleration rates, cars are more likely to hit cars and trucks in MVCs. Despite the low percentage, truck-involved crashes cannot be ignored because of their high severity. By comparing Type I and II crashes, it can be found there is a higher percentage of truck-involved crashes for Type II crashes than Type I crashes.

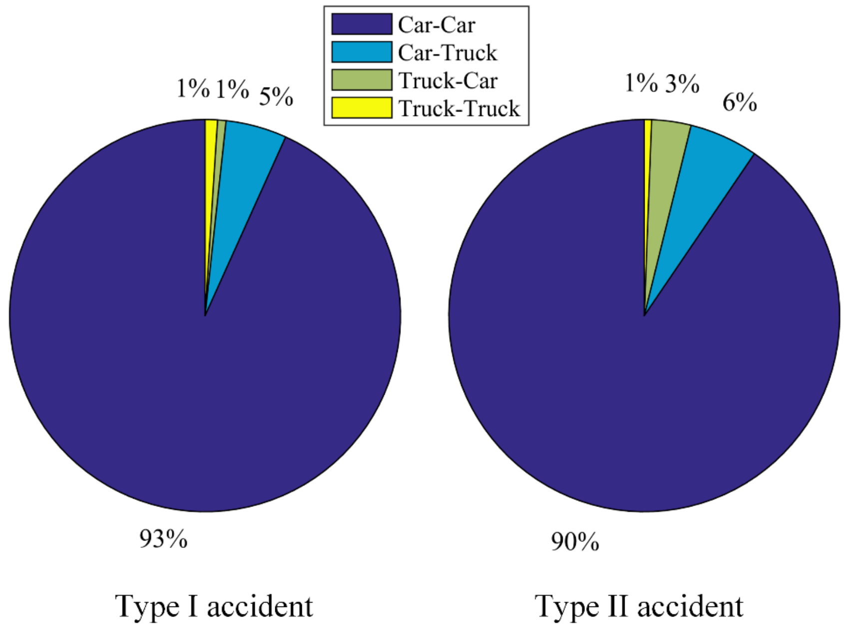
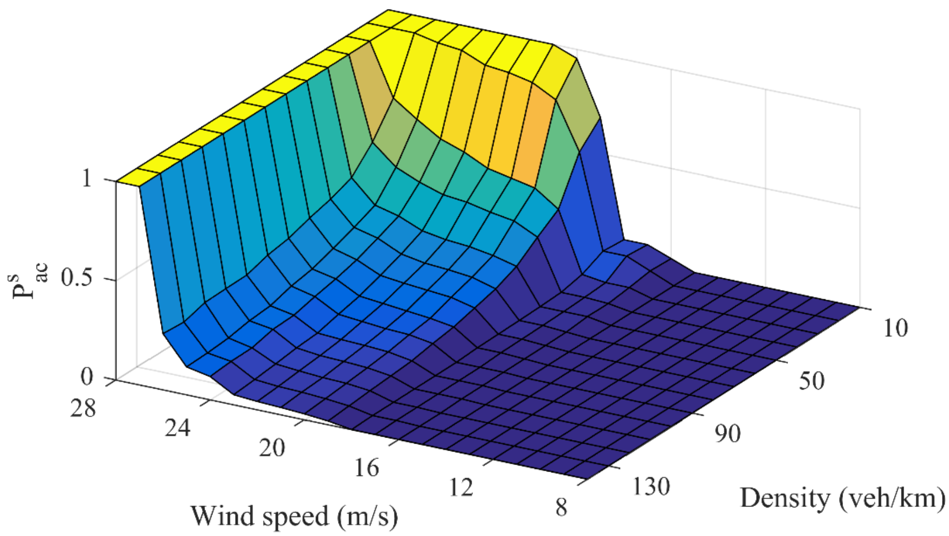


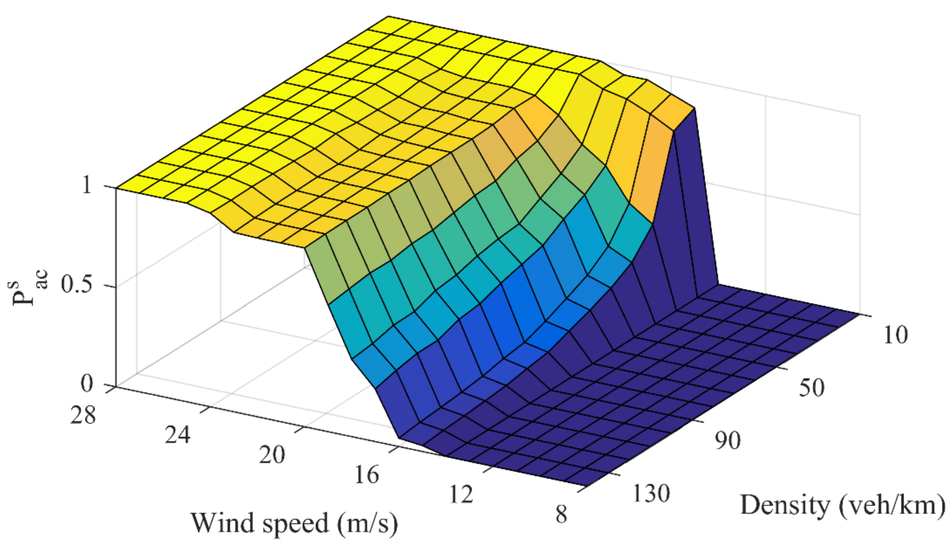
Figure 3.5 Proportion of MVCs involved different vehicle types under snowy weather

3.1.3 Single-vehicle Crashes

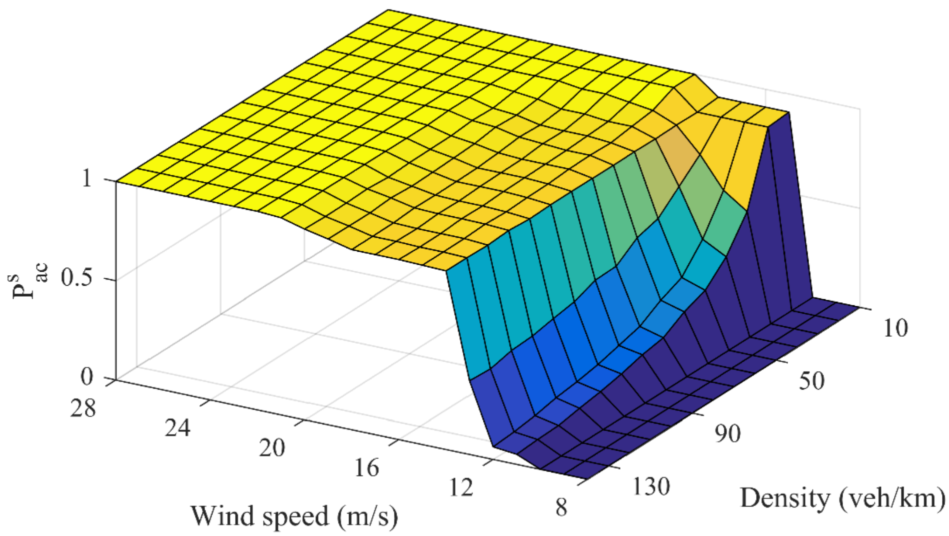
Strong wind, together with other adverse weather conditions, such as rain and snow, contributes significantly to single-vehicle crashes (SVC). SVCs in work zones under combined weather conditions, including strong crosswinds and different road surfaces, are studied. The proposed framework is used to calculate the probability of an SVC. Figure 3.6 shows the probability of an SVC P_{ac}^{s} under different weather conditions. It is found that P_{ac}^{s} increases with the increase of wind speed and decrease of traffic density under different weather conditions. Since the decrease of traffic density usually leads to the increase of vehicle speeds in the traffic flow, both higher wind speeds and lower traffic density/higher vehicle speeds lead to larger wind forces acting on vehicles, which in turn contribute to higher crash probability. By comparing Figures 3.6(a), (b), and (c), it can be found that snowy weather poses the greatest threat to single-vehicle safety, whereas the clear weather does the least. For example, when the wind speed is 19 m/s and the traffic density is 40 veh/km, the probabilities of an SVC P_{ac}^{s} under clear, rainy, and snowy conditions are 0.279, 0.798, and 0.987, respectively.



(a) Clear



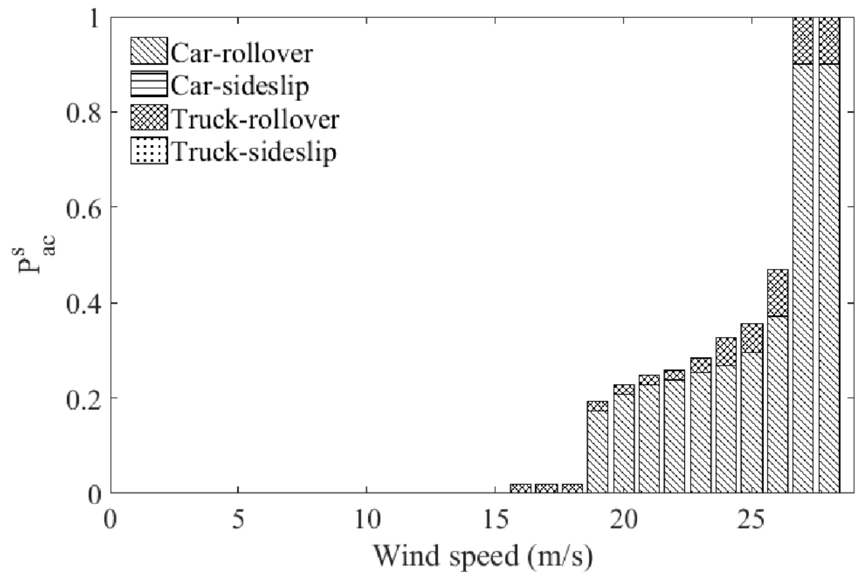
(b) Rainy



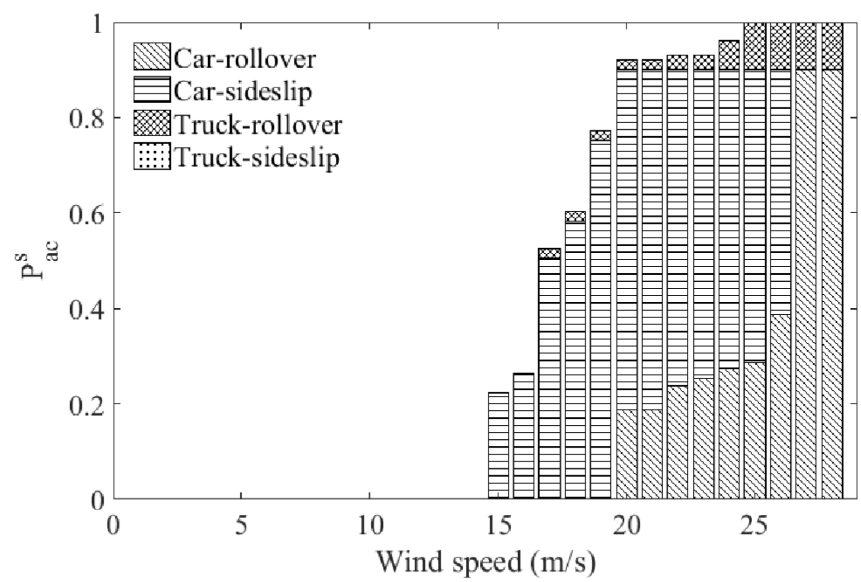
(c) Snowy

Figure 3.6 SVC probability under different weather conditions

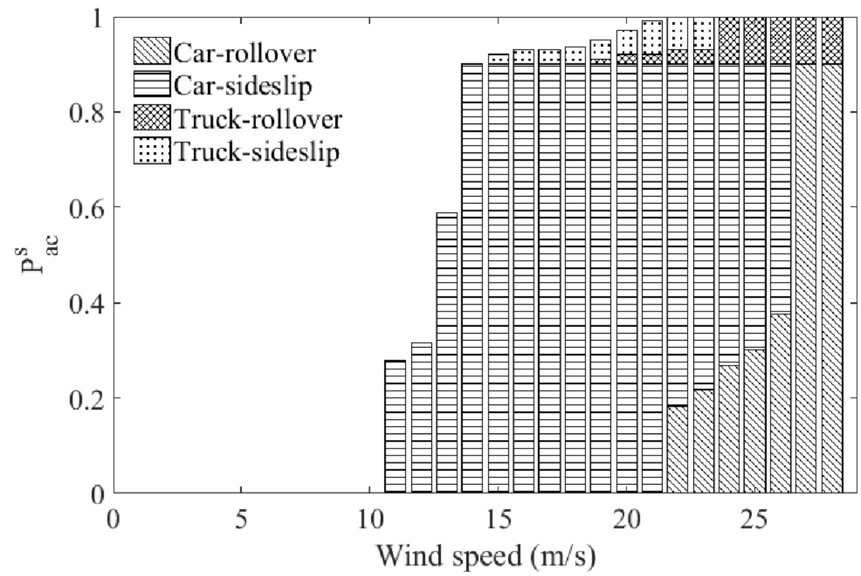
Because of various dynamic and static characteristics, different types of vehicles have varying safety performance even under the same hazardous condition, which is studied in this section. Figure 9 gives the probabilities of different SVC types under different weather conditions when the traffic density is 50 veh/km. It can be found in Figure 9(a) that rollover crashes are dominant on dry road surfaces during clear weather for both cars and trucks. Moreover, trucks are found to more likely roll over than cars. For example, trucks begin to roll over at a wind speed of 16 m/s, while cars begin to roll over at a wind speed of 19 m/s. This is likely because trucks have a higher center of gravity and larger frontal area. During rainy weather, cars are prone to sideslip crashes when the wind speed is not very high, as shown in Figure 3.7(b). When the wind speed is relatively high, rollover crashes are dominant for cars. Similar to the case of clear weather, trucks are only vulnerable to rollover crashes rather than sideslip crashes during rainy weather. It can be seen from Figure 3.7(c) that, for both cars and trucks under snowy weather conditions, sideslip crashes dominate when the wind speed is not very high, and rollover crashes prevail when the wind speed is relatively high. Because of low friction on snowy road surfaces, cars and trucks can experience sideslip crashes at a relatively low wind speed, i.e., 11 m/s and 15 m/s, respectively. It is also found that cars are more vulnerable to sideslip than trucks likely because of their lighter weights. For example, cars start to sideslip at a lower wind speed than trucks (i.e., 11 m/s vs 15 m/s). Moreover, under the wind speed of 14 m/s, all cars, i.e., 90% of vehicles in the traffic flow, experience sideslip crashes, while there is no occurrence of sideslip for trucks.



(a) Clear



(b) Rainy



(c) Snowy

Figure 3.7 Probability of different SVC types under different weather conditions

3.1.4 Work Zone Safety Assessment

Finally, by setting the clear weather condition as the baseline scenario, crash related indexes defined previously under rainy and snowy weather conditions are calculated. The individual vulnerability indexes of MVCs and SVCs during rainy weather are 3.41 and 2.13, while those during snowy weather are 7.83 and 2.94, respectively. This indicates that crash vulnerability under snowy weather conditions is higher than that under rainy conditions for both MVCs and SVCs. In addition, MVCs are more likely influenced by adverse weather than SVCs, as reflected by higher crash vulnerability. Throughout this study, the weight parameter θ in Eqn. (8) was set as 0.5 simply for demonstration purposes by assuming MVCs and SVCs have equal contributions to the overall work zone safety risk. The integrated risk indexes during rainy and snowy weather are calculated with Eqn. (8) as 2.77 and 5.39. This suggests that rainy and snowy weather are 1.77 and 4.39 times more likely to cause crashes at work zones, respectively, as compared with clear weather. This finding is inconsistent with previous observations in statistical studies by Zhao and Garber (2001) and Harb et al. (2008) that most work-zone crashes occur in clear weather conditions. However, these observations were backed by some assumptions, i.e., most work zone construction activities are conducted under favorable weather conditions, or drivers are generally more vigilant during inclement weather. It is clear that the validity of both assumptions is dependent on specific locations, construction policies, and driver groups. Due to the lack of stronger supporting evidence and data, it is believed that more studies are still required in order to investigate the inconsistency between the simulation-based approach and statistical approach.

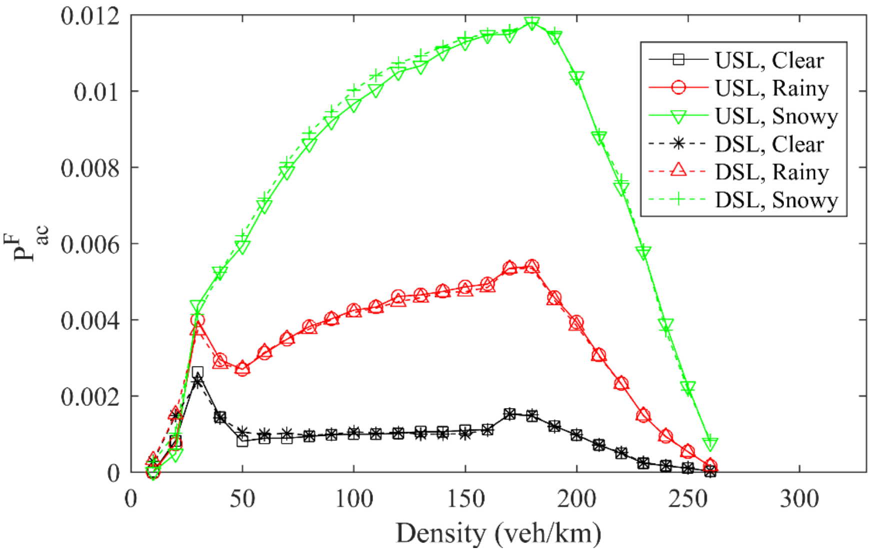
3.2 The Effect of DSL on Work Zone Traffic Safety

Although there has been controversy in terms of the effect of a differential speed limit (DSL) on traffic safety, DSLs have been adopted on many interstate highways in many U.S. states, such as California, Oregon, Washington, Idaho, Montana, Arkansas, Indiana, and Michigan. Typically, lower speed limits are set for trucks and buses to avoid serious overturn or sideswipe or losing control under adverse conditions such as inclines, downgrades, and extreme curves in the road. However, some studies indicate that a higher variance of vehicle speeds in traffic flow may increase the MVC risk (e.g., Duncan et al. 1998). In this section, the effect of DSLs on multi-vehicle and single-vehicle safety in work zones are studied (Table 3.2). Under a DSL, the speed limit of trucks is 10 mph (6.5 m/s) lower than that of cars in the normal area in this study. Meanwhile, speed limits of cars and trucks in the work zone area are the same and are also equal to that of trucks beyond the work zones (normal roads). The DSL scenario will be compared with the uniform speed limit (USL) scenarios studied in the previous section.

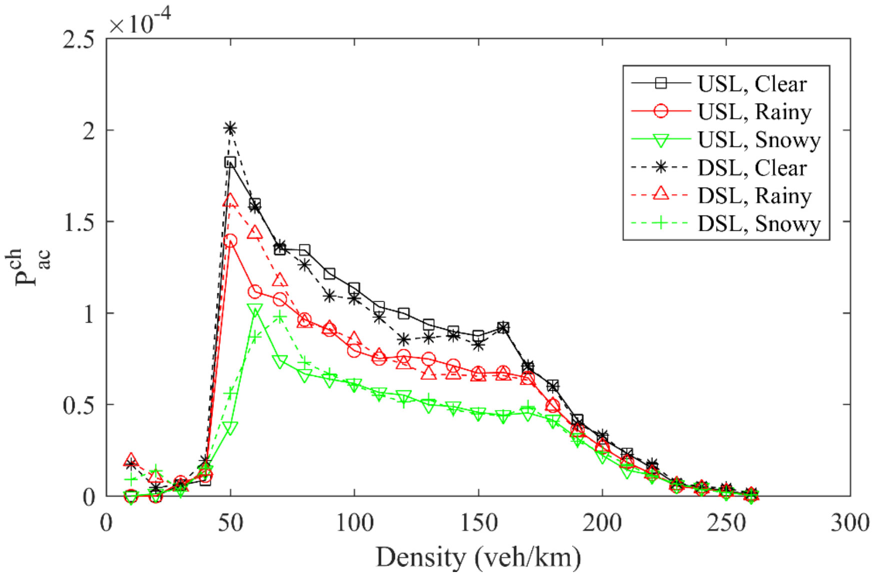
Table 3.2 Maximum velocity in the DSL scenario under different weather conditions

Weather condition	Maximum velocity (m/s)			
	Normal area		Work zone area	
	Car	Truck	Car	Truck
Clear	33.5	29	29	29
Rainy	30	25.5	25.5	25.5
Snowy	23.5	19	19	19

Figures 3.8(a) and (b) present the probability of an MVC caused by abrupt deceleration and lane change, P_{ac}^{F} and P_{ac}^{ch}, under different weather conditions, respectively. Figure 10(a) shows that the probabilities of Type I crashes of DSL and USL scenarios are very close under different weather conditions. However, the DSL scenario has a slightly higher maximum probability of Type II crashes than the USL scenario under clear and rainy weather conditions, as shown in Figure 3.8(b). The DSL does not cause a significant speed difference between trucks and cars when the traffic density is high because the desired speed cannot be reached due to the limited headway. When the traffic density is relatively low, DSL can reduce truck speeds. Meantime, there are also relatively fewer chances of potential conflict between vehicles under low traffic density, which limits the occurrence of MVCs. Therefore, the resultant impact of a DSL on MVC probability becomes insignificant.



(a) Type I crash

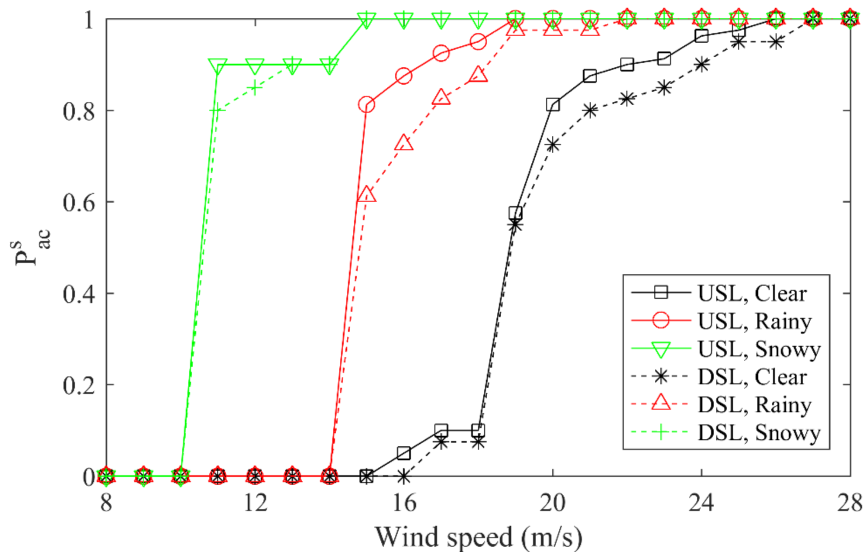


(b) Type II crash

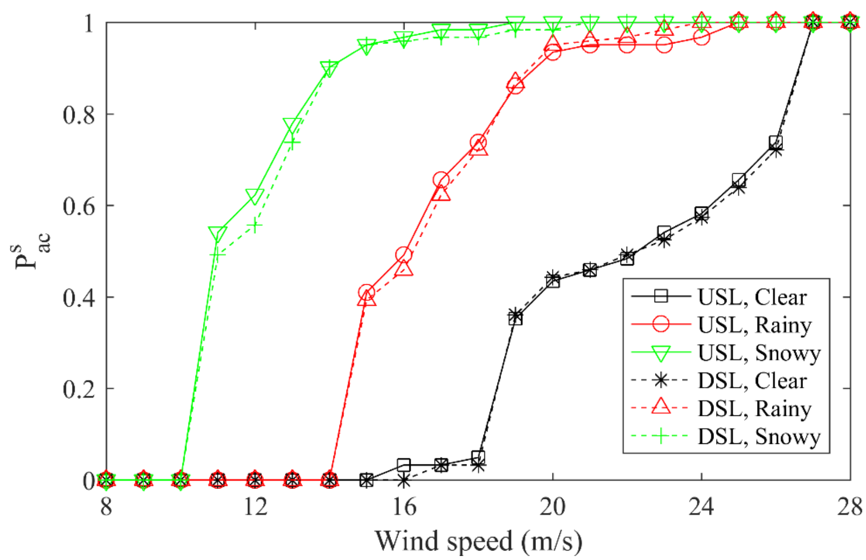
Figure 3.8 MVC probability with USL and DSL

According to the simulation results, a DSL is found to have considerable effect on single-vehicle safety when the traffic density is low, i.e., $\rho \leq 20$ veh/km. Figure 3.9 shows the SVC probability under USL and DSL when the densities are 20 and 30 veh/km. Figure 3.9(a) shows that the SVC probability of the DSL scenario is generally lower than that of the USL scenario under three different weather conditions when the traffic density is 20 veh/km. However, when the traffic density is increased to 30 veh/km, the SVC probabilities of both scenarios are very close, as shown in Figure 3.9(b). This can be explained by the change of vehicle velocity due to the adoption of DSLs under different traffic densities.

Figure 3.10 gives the mean velocity of cars and trucks under USLs and DSLs during rainy weather. When the traffic density is lower than 20 veh/km, a DSL leads to a significant speed reduction for both trucks and cars, which further reduces the SVC risk (Figure 3.10). However, when the traffic density is relatively high, the influence of a DSL on vehicle speeds is very limited. Although truck speed under a DSL is lower than that under a USL, the overall crash probability does not change too much due to its low proportion.



(a) $\rho = 20$ veh/km



(b) $\rho = 30$ veh/km

Figure 3.9 SVC probability under USLs and DSLs

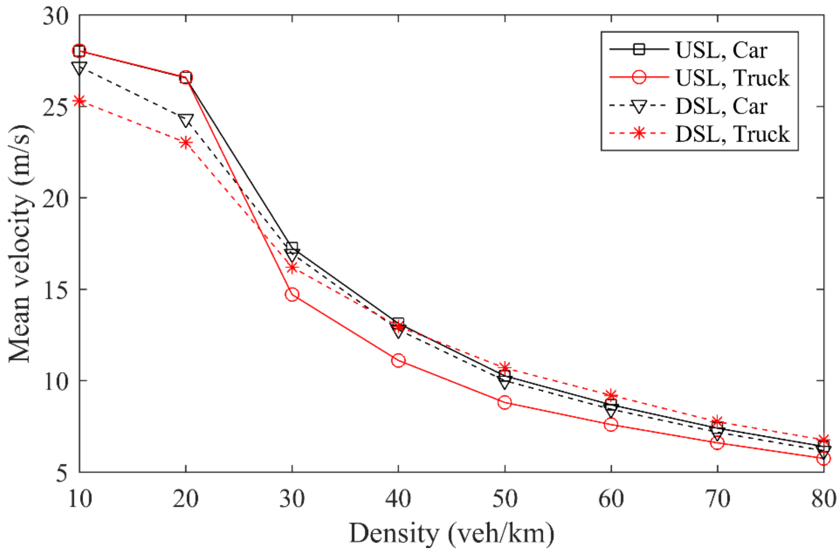


Figure 3.10 Mean velocity of cars and trucks under USLs and DSLs during rainy weather

The integrated risk index RI and individual vulnerability index VI under USLs and DSLs are calculated and given in Table 3.3. Similar to the previous section, the baseline scenario is the work zone traffic with a USL under clear conditions. For the convenience of comparison, all the data are scaled with the values of RI, VI^m, and VI^s for the baseline scenario being 1.0. Table 3.3 shows that a DSL generally leads to a slight increase in the MVC vulnerability and a slight decrease in the SVC vulnerability under different weather conditions. As a result, the effect of DSLs on the overall work zone crash risk is found to be insignificant.

Table 3.3 Risk index and vulnerability indicator under USLs and DSLs

Index		Clear	Rainy	Snowy
RI	USL	1.00	2.77	5.39
	DSL	1.02	2.76	5.45
VI^m	USL	1.00	3.41	7.83
	DSL	1.04	3.40	7.96
VI^s	USL	1.00	2.13	2.94
	DSL	0.99	2.12	2.94

3.3 The Effect of Truck Ratio on Work Zone Traffic Safety

The proportion of trucks in the traffic flow is known to have significant impact on work zone crashes, due to their unique characteristics such as large size and limited maneuverability. In this section, the effect of truck ratio on traffic safety will be investigated. Three cases with different truck ratios are studied: R_t= 0.1, 0.2, and 0.3. The integrated risk index RI of the three cases with different truck ratios are shown in Figure 3.11, which shows that the truck ratio increase leads to the decrease in the crash risk in rainy and snowy weather. For example, as the truck ratio increases from 0.1 to 0.3, the integrated risk index RI decreases by 14.4% in rainy weather and 23.6% in snowy weather. However, the truck ratio has very little effect on clear weather. Figure 3.12 gives the individual vulnerability index VI of MVCs and SVCs for different truck ratios. It is found that the individual vulnerability index of both MVCs and SVCs, VI^m and

VI^s, generally decreases as the truck ratio increases. However, MVCs are much more sensitive to the truck ratio than SVCs.

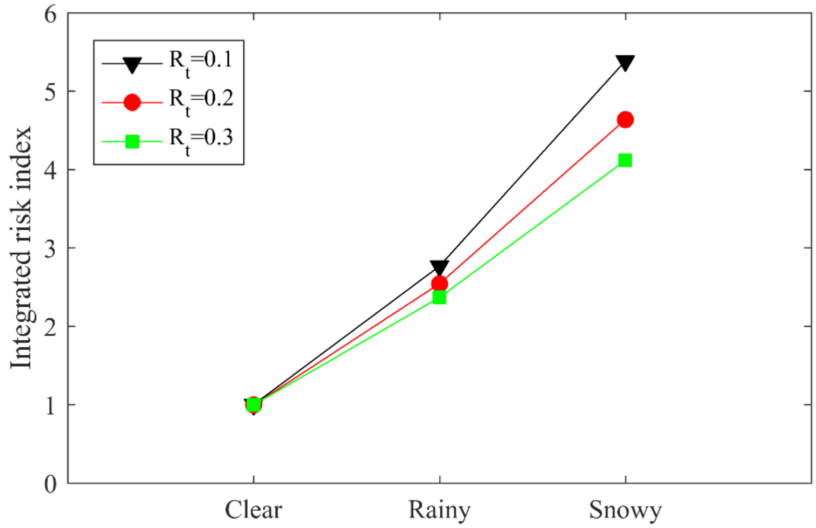


Figure 3.11 Integrated risk index for different truck ratios

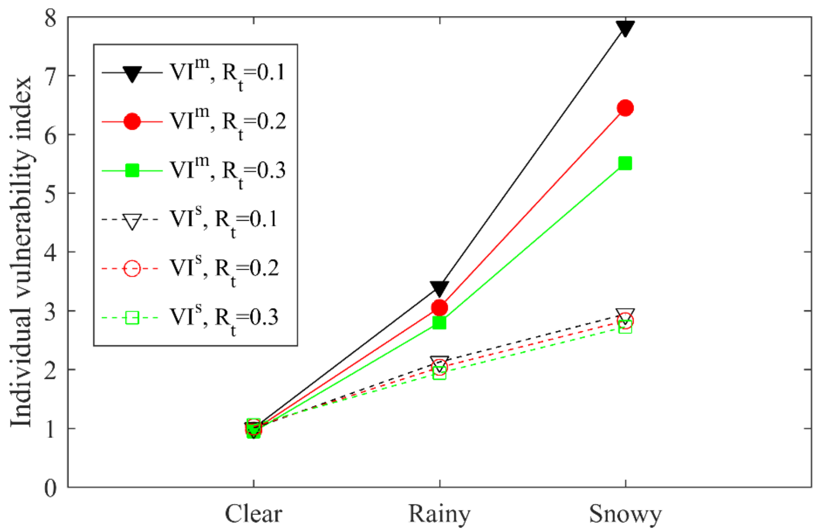


Figure 3.12 Individual vulnerability index for different truck ratios

Because the overall crash risk is significantly influenced by the variation of the truck ratio through affecting MVCs, and Type I crashes dominate MVCs, the probability of Type I crashes is further investigated here. We take Type I crashes occurring in snowy weather as an example and present the crash probability in Figure 3.13. It is found that the increase of the truck ratio affects Type I MVC probability in two ways. First, the maximum crash probability decreases as the truck ratio increases. This can be explained by the fact that trucks have higher acceleration and deceleration rates than cars. A higher truck ratio leads to smaller overall velocity fluctuation of the traffic flow, which further results in smaller Type I crash probability. Second, the maximum traffic density decreases as the truck ratio increases. This is because trucks have larger lengths than cars, and a higher truck ratio leads to smaller traffic density. Because of these two effects, Type I MVC probability decreases greatly with the increase of the truck ratio.

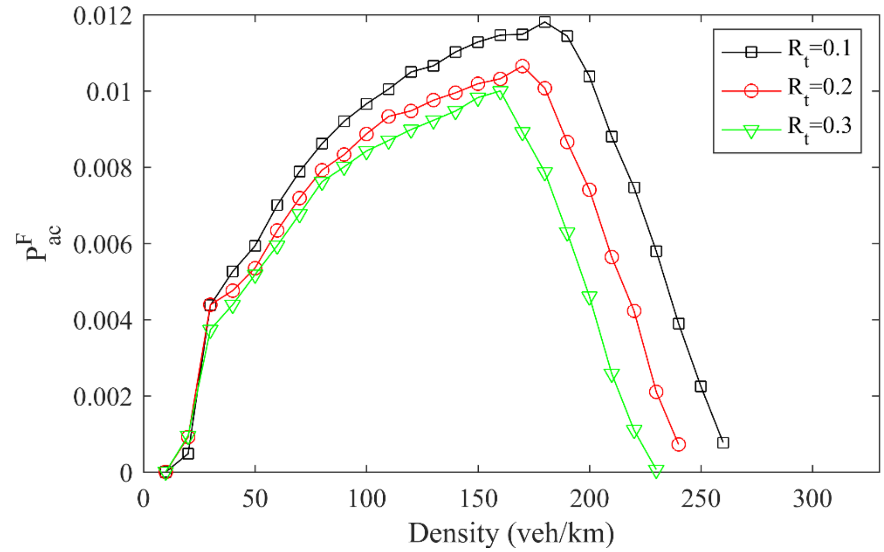


Figure 3.13 Type I MVC probability for different truck ratios in snowy weather

The probability of SVCs is studied to provide more details regarding the effect of the truck ratio on SVCs. According to the simulation results, the truck ratio impacts the probability of SVCs under different traffic densities in a similar way. Therefore, a traffic density of 50 veh/km is selected for the purpose of discussion. Results shown in Figure 3.14 are consistent with those in Figure 3.12. As the truck ratio increases, SVC probability P_{ac}^{s} generally decreases during rainy and snowy weather while P_{ac}^{s} increases only slightly in clear weather. This can be explained by different crash vulnerabilities of cars and trucks under different road surface conditions. According to the study by Hou et al. (2019a), on wet and snowy road surfaces, sideslip dominates SVCs when the wind speed is not very high. Meanwhile, trucks are generally less likely to sideslip than cars. Therefore, SVC probability decreases with the increase of the truck ratio under rainy and snowy weather conditions. In contrast, rollover crashes are found to be dominant on dry roads while trucks just have slightly higher rollover vulnerability than cars. As a result, an increase of the truck ratio only leads to a slight increase in SVC probability in clear weather.

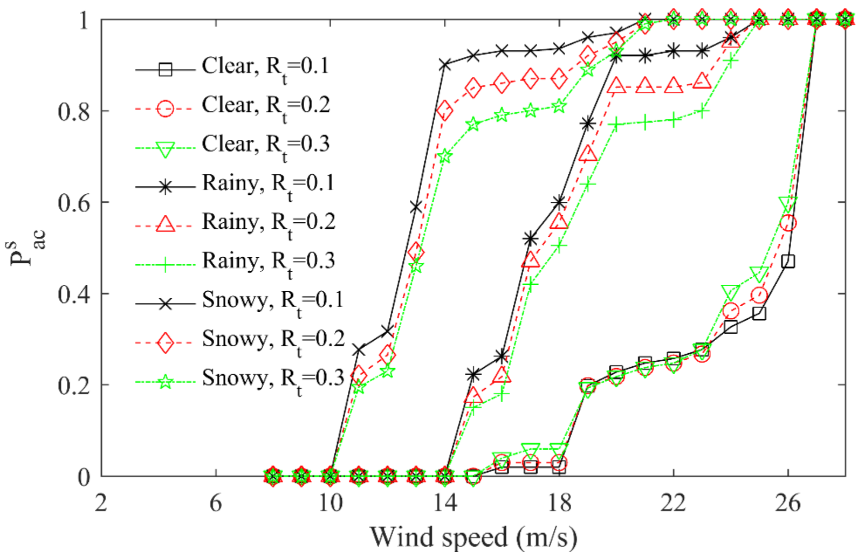


Figure 3.14 SVC probability for different truck ratios

4. CONCLUSIONS

In this study, an integrated simulation framework has been developed for evaluating traffic safety in work zones under adverse weather conditions. For the first time, the proposed framework is able to comprehensively evaluate both multi-vehicle and single-vehicle safety of stochastic traffic flow in work zones by considering different work zone configurations, weather conditions, and road surface conditions. An integrated risk index that can consider the effect of both MVCs and SVCs was introduced to evaluate the traffic safety of work zones under adverse weather conditions. In the demonstrative study, traffic safety of a typical work zone under different weather conditions was investigated. The effects of DSLs and truck proportion on work zone traffic safety were studied. The main findings of this study can be summarized as follows:

(1) Work zone capacity reductions caused by rain and snow are 8.6% and 20.1%, respectively, which are consistent with the findings in existing studies.

(2) Rainy and snowy weather leads to an increase in the probability of Type I MVCs (caused by abrupt deceleration) but a decrease in the probability of Type II MVCs (caused by lane change).

(3) Type I and II MVCs have different distribution patterns of crash location: Type I crashes happen throughout the entire congested area while Type II crashes mainly happen upstream of the congested area.

(4) The SVC probability under rainy and snowy weather conditions is higher than that under clear weather. The types of SVCs vary with weather conditions and wind speeds. Rollover crashes are dominant during clear weather. Under snowy weather conditions, sideslip crashes dominate when the wind speed is not high, while rollover crashes prevail when the wind speed is relatively high.

(5) The overall crash risk of work zones under rainy and snowy weather conditions is higher than that under clear conditions, which is inconsistent with previous observations that most work-zone crashes occur in clear weather conditions. Due to the lack of supporting evidence, more studies are still needed in order to explain the inconsistency between the simulation-based approach and statistical approach.

(6) DSLs generally lead to a slight increase in MVC vulnerability and slight decrease in SVC vulnerability under different weather conditions. As a result, the effect of DSLs on the overall work zone crash risk is insignificant.

(7) An increase of the truck ratio leads to a decrease in the crash risk in rainy and snowy weather while it has very little effect in clear weather.

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