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RELIABILITY-BASED SAFETY RISK AND COST PRODUCTION OF LARGE TRUCKS ON RURAL HIGHWAYS

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ABSTRACT

The primary causes of accidents involving large trucks on rural highways were found to be excessive speed and adverse driving conditions. Different from passenger vehicles, it is known that the safety performance of large trucks in adverse driving conditions greatly depends on the specific terrain and local weather conditions. By integrating both historical data analysis and simulations, a multi-scale investigation is conducted to evaluate the traffic safety of large trucks on mountainous interstate highways. Firstly, the ten-year historical accident records are analyzed to identify the accident-vulnerable-locations (AVLs) and site-specific critical adverse driving conditions. Secondly, a simulation-based single-vehicle assessment is performed for predicting the large-truck accident risks with the combination of given weather, topographical, road, and vehicle information at those AVLs along the entire corridor. A framework of a reliability-based assessment model of vehicle safety under adverse driving conditions is developed. Such a framework is built based on the advanced transient dynamic vehicle simulation models, which can consider the coupling effects between vehicles and adverse driving conditions, such as wind gust, snow-covered or icy road surfaces and/or curving. The single-vehicle safety index is introduced to provide rational assessment of accident risks by considering uncertainties of critical variables. Finally, GIS maps with topographic conditions embedded are generated. By displaying the data on the GIS-based map, different accident risk indices can easily be displayed and compared on the GIS map. A typical mountainous highway in Colorado is studied for demonstration purposes.

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EXECUTIVE SUMMARY

Extensive works have been conducted on traffic safety and injury prevention related to multi-vehicle accidents of large trucks in past decades (e.g., Braver et al. 1997, Chang and Mannering 1999, Lyman and Braver 2003). Different from most passenger vehicles, which are dominantly vulnerable to multi-vehicle traffic conflicts, large trucks are also prone to single-vehicle accidents on the mountainous interstate highways due to the complex terrain and fast-changing weather (USDOT 2005, Baker 1991). Although the absolute number of single-vehicle accidents is typically smaller than that of multi-vehicle accidents, single-vehicle accidents have caused serious injury and casualty (The National Academies 2006). For example, single-vehicle accidents were responsible for 57.8% of the total fatalities of traffic accidents in 2005 (USDOT 2005). This is especially true when complex terrain is coupled with inclement weather conditions, such as snow, ice, or strong wind. Each year in the United States, it is found that adverse weather alone is associated with more than 1.5 million vehicular accidents, which cause 800,000 injuries and 7,000 fatalities (The National Academies 2006).

In the present study, an attempt is made to integrally evaluate the safety of large trucks on mountainous highways. The I-70 corridor in Colorado is chosen to demonstrate the methodology because of its typical mountainous terrain and adverse weather conditions. Firstly, the ten-year historical accident records are analyzed to identify the accident-vulnerable-locations (AVLs) and site-specific critical adverse driving conditions. Secondly, simulation-based single-vehicle assessment is performed for predicting the large truck accident risks with the combination of given weather, topographical, road, and vehicle information at those AVLs along the whole corridor. A framework of a reliability-based assessment model of vehicle safety under adverse driving conditions is developed. Such a framework is built based on the advanced transient dynamic vehicle simulation models, which can consider the coupling effects between vehicles and adverse driving conditions, such as wind gust, snow-covered or icy road surfaces and/or curving. The single-vehicle safety index is introduced to provide a rational assessment of accident risks by considering uncertainties of critical variables. Finally, GIS maps with topographic conditions embedded are generated. By displaying the data on the GIS-based map, different accident risk indices can easily be displayed and compared on the GIS map.

1. INTRODUCTION

1.1 Background

The rural roads of the nation serve as a critical link in the transportation system around the country and provide access from urban areas to the nation's heartland. In America, there are about 60 million people in rural areas, where rural roads provide the primary routes of travel, agricultural production, forest services, commerce, and tourism (The Road Information Program 2005). Despite the fact that only 39.4% of miles traveled by all vehicles are in rural areas, about 68.4% of crash fatalities occur in rural highways (FHWA Highway Statistics 1998). According to the fatality analysis reporting system (FARS) by the National Highway Traffic Safety Administration (NHTSA), 57.8% of fatal accidents that occurred in the United States in 2005 were single-vehicle accidents and about 53.6% of fatal accidents happened on rural roads. According to the Large Truck Crash Causation Study (LTCCS) database, nearly 27% of all crashes involved with large trucks were non-collision single-vehicle crashes. Understanding and mitigating single-vehicle safety risks for large trucks is an important topic for rural transportation and is the focus of the proposed study.

There are many causes of single-vehicle accidents of large trucks on rural roads. Many studies suggest that the dominant causes are excessive speed and adverse environments (The Road Information Program 2005). Nationally, according to FARS, when the speed limit is 45-50 mph for both urban and rural roads, the fatal accident numbers are close (urban road 50% and rural roads 44% of total fatal accidents). When the speed limit becomes 55 mph for both roads, fatal accidents for rural roads increase dramatically to 77.89% while those on urban roads only account for 18.46% of total fatal accidents (data from FARS database for 2005). In midwest mountainous states, single-vehicle accidents are more complicated due to the uniqueness of the adverse environments. Specifically, inclement windy weather, rough road surface profiles, and hilly topographic conditions (e.g., sharp curves and steep grades) among others, are often blamed for these accidents in mountainous areas. The inclement weather in mountainous areas includes strong gusts, rain, and snow storm. The ice- and snow-covered roads can further challenge drivers. These driving conditions, coupled with (negative) driver behavior, significantly increase the risk for single-vehicle accidents for large trucks on rural roads. It has been reported that many large trucks have experienced serious accidents due to sudden wind gusts, hilly terrain and rapidly changing weather, such as on I-25, I-70, and I-80 to Wyoming. These large-truck accidents not only threaten the lives of truck drivers, but also endanger other vehicles and drivers nearby. The uniqueness of adverse environments on rural roads in mountainous states warrants an investigation in order to reduce crashes associated with trucks and protect drivers from injury. Despite serious risks of trucks in mountainous states, there are very limited resources available to assess the risks and associated costs of vehicle accidents on rural highways which can be used for the transportation management agencies and truck industry to assess the risks associated with fleet, plan the trip, and make reasonable decisions when adverse conditions exist.

1.2 Problem Statement

Single-vehicle crashes under adverse conditions or hazardous environments were found to be closely related to the coupling between vehicles, infrastructure, and environment (Baker 1991, Guo and Xu 2006, Chen and Cai 2004, Chen et al. 2009). As a result of this unique coupling, observations solely from historical crash data in one place can hardly be translated into accurate risk prediction in different locations or under driving environments that were not covered by the actual crash data. Therefore, in addition to analyzing actual historical crash data gathered after the crashes, investigations of single-vehicle crashes also require a reasonable simulation model that can be used for more than after-the-fact reconstruction of the crash (TRB 2007); more importantly, to reasonably predict the potential risk of crashes under comprehensive scenarios, including those which may not be covered by historical crash data.

In automobile engineering, significant efforts have been made for simulating vehicle dynamics and accidents with engineering simulation models, including the simple rigid body model, the bicycle model, and the complicated spring-mass multiple-degree-of-freedom model (Thomas 1992). Despite extensive works in these fields (e.g., Winkler and Ervin 1999, Gaspar et al. 2004, 2005, Sampson 2000), research on vehicle accident risks, which considers the coupling between the vehicle dynamic model, inclement weather, and topographical condition, is still very limited. Baker (1986, 1987, 1991, 1994) was the first researcher who tried to investigate the high-sided vehicle accident risks under a strong crosswind. In his studies, vehicle accident risks were assessed through solving several static equilibrium equations with some predefined accident criteria. Based on Baker's work, several reliability-based accident assessments were recently conducted (Sigbjornsson and Snaebjornsson 1998, Sigbjornsson et al. 2007). Chen and Cai improved the accident risk assessment by introducing a general dynamic interaction model, based on which the vehicle accident assessment was conducted by considering excitations from the supporting structure (e.g., bridge). Guo and Xu introduced an integrated vehicle safety assessment model on bridges. In the model, the dynamic bridge-vehicle-wind interaction analysis, as well as the safety assessment, was carried out at the same time using the same accident criteria as Baker (1991). In most existing studies, however, only situations in which vehicles are driven on straight routes with only crosswind excitation were considered. As a result, these models can hardly serve as a general methodology which can accurately replicate various driving environments as well as associated uncertainties in nature.

1.3 Research Objectives

This study will provide a framework to assess the risks and associated costs of single-vehicle accidents involving large trucks in mountainous states such as Colorado, considering the unique adverse environments. Simulation-based single-vehicle assessment is performed for predicting the large-truck accident risks with the combination of given weather, topographical, road, and vehicle information. A framework of a reliability-based assessment model of vehicle safety under adverse driving conditions is developed. Such a framework is built based on the advanced transient dynamic vehicle simulation models, which can consider the coupling effects between vehicles and adverse driving conditions, such as wind gusts, snow-covered or icy road surfaces and/or curving. The single-vehicle safety index is introduced to provide a rational assessment of accident risks by considering the uncertainties of critical variables. By applying the reliability theory, the proposed framework can consider the uncertainties associated with the coupled problem of adverse environmental conditions and driver behavior. Also, GIS maps with topographic conditions embedded are generated.

2. HISTORICAL ACCIDENT DATA ANALYSIS OF I-70 IN COLORADO (CHEN ET AL. 2010)

2.1 I-70 Interstate Corridor

The Interstate I-70 mountain corridor within Colorado, from Denver to Grand Junction, is a typical mountainous highway in rural areas as it is a gateway to recreation, commerce, and everyday necessities for Colorado residents and visitors. At some locations along the corridor, very steep grades, which are coupled with extreme weather conditions have been blamed for many accidents involving large trucks. Differential speed limits have been adopted at several locations where the terrains are complicated on the I-70 mountain corridor. Ten-year (1996-2005) historical accident data of I-70 in Colorado from Vail to Golden (milepost 179.90 to 258.60) were studied. In 2005, the percentage of trucks in traffic on this corridor was 5.7%-13%. Average daily traffic (ADT) on I-70 in Colorado is 32,962. During the ten-year period, there were 1,565 accidents reported involving trucks, out of which 762 and 639 accidents involved large trucks/buses as the first vehicle (vehicle 1) and another vehicle (vehicle 2), respectively.

2.2 Data Analysis and Accident Vulnerable Locations (AVL)

Based on the comprehensive analysis of the historical accident data on the I-70 corridor between 1996 and 2005, some accident vulnerable locations (AVL) that experience a considerable number of past accidents are summarized in Table 2.1. AVLs are selected based on the number of accidents occurring on each segment (typically 0.1 mile long), which is identified with the beginning and ending mileposts (MP) (e.g., MP 184.4-185.4). Due to limited space, Table 2.1 only gives detailed information for several selected AVLs, including the MPs, the numbers of accidents associated with different vehicle types, accident types, geometric conditions, speed limits, and adverse weather conditions. Most differential speed limits on I-70 are applied in the westbound direction, as shown in column 4 in Table 2.1. "No. of truck-initiated accidents (percent of all accidents)" (column 5) is the number (and percentage) of accidents with large trucks (more than 10k lbs) as the first vehicle (vehicle 1). Column 6 shows the number of accidents occurring at different adverse road surface conditions (e.g., wet, icy, or snowy). Column 7 gives the number of accidents by accident type: single-vehicle accidents, including overturn and sideswipe accidents, and typical multi-vehicle accidents (rear-end accidents). By comparing the actual driving speeds reported in the accident record with the corresponding speed limits, the percentage of those trucks driving at least 10 mph over the speed limit in the truck-initiated accidents was given in Column 8.

Some general observations from the accident data analysis of I-70 AVLs include: (1) trucks were more vulnerable to accidents than other vehicles (around 50%-70% of all accidents were initiated by trucks); (2) for multiple-vehicle accidents, rear-end collisions were dominant (over 80%); (3) adverse road surface conditions were found to have significant impacts on traffic safety (associated with up to 70% of accidents); and (4) dominant accident types at different locations were sideswipe or overturn accidents (single-vehicle), rear-end accidents (multi-vehicle), or both. Based on these observations, the need and significance of the present study focusing on trucks and adverse driving conditions are well justified.

Table 2.1 Selected Accident Vulnerable Locations (AVLs) on I-70 (1996-2005

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Milepost Range	Terrain features	Grade	Speed limit (mph)	No. of truck-Initiated accidents (% of all accidents)	No. of accidents under adverse road surface conditions	Accident Types	Percentage of trucks over speed limits by 10 mph or more
184.4-185.4	Curve R=1250 ft	6%	Truck 45 Others 65	24 (64.9%) EB3, WB21	Wet 2 Icy 13 Snowy 7	Overturn 0 Sideswipe 11 Rear-end 7	8.3%
204.8-205.14	Curve R=2130 ft	8%	Truck 30 Others 60	13 (56.5%) EB6, WB7	Wet 3 Icy 4 Snowy 2	Overturn 0 Sideswipe 5 Rear-end 4	38.5%
208.0-209.3	Straight	8%	Truck 30 Others 60	36 (69.2%) EB2, WB34	Wet 1 Icy 2 Snowy 5	Overturn 8 Sideswipe 8 Rear-end 12	86.1%
213.0-214.0	Straight	8%	Truck 30 Others 60	19 (48.7%) EB7,WB12	Wet 3 Icy 3 Snowy 12	Overturn 0 Sideswipe 12 Rear-end 10	0%
242.5-242.92	Curve R=690 ft	4%	All 55	18 (69.3%) EB12, WB6	Wet 3 Icy 5 Snowy 1	Overturn 8 Sideswipe 5 Rear-end 2	33.3%
243.4-244.7	Curve R=850 ft.	4%	All 55	44 (70.3%) EB28, WB16	Wet 6 Icy 5 Snowy 1	Overturn 15 Sideswipe 11 Rear-end 7	22.2%
250.8=251.2	Curve R=1540 ft.	3%	All 65	7 (58.3%) EB0, WB7	Wet 2 Icy 3 Snowy 2	Overturn 1 Sideswipe 4 Rear-end 2	0%

Note: EB=east bound vehicles; WB=west bound vehicles; R=curve radius

2.3 Accident Analysis under Adverse Driving Conditions

Historical accidents are first studied for different adverse driving conditions, such as wind, snowy, and icy road surfaces and different terrains. Among all the adverse driving conditions, Figures 2.1-2.3 provide statistics of historical accidents involving trucks under several of the most significant adverse driving conditions on I-70, including strong winds, snow- and ice-covered road surfaces, and on grades, respectively. Different dot sizes on the maps represent different numbers of similar accidents happening at the same locations during the past ten years, as defined in the legend.

Figure 2.1 indicates that there are about 30 accidents identified as wind-induced in the accident records during the ten-year period. It is noted that the actual number may be higher since it is possible that some accidents were not identified as wind-induced on the accident report despite the fact that wind may also contribute to the accidents along with other reported factors. According to Figure 2.1, except for some scattered locations along I-70, most of the wind-induced accidents happened in the east portion of the corridor. Repetitive accidents happened at several locations along I-70, such as MP 229, 244, and 250-252.

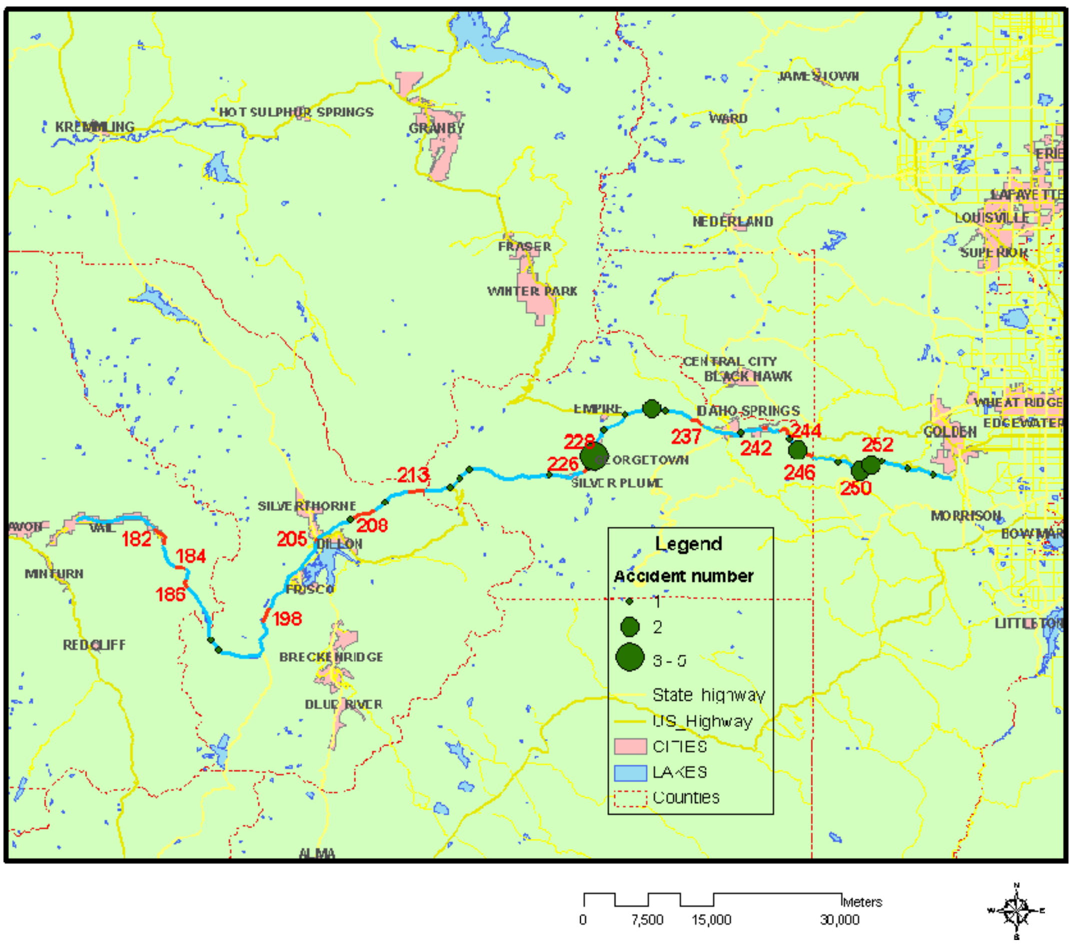


Figure 2.1 Historical Wind-induced Accidents (1996-2005)

In Figure 2.2, the historical accidents happening on snow-covered roads are displaced. A large number of repetitive accidents happened frequently along the whole stretch between MP 182 and 228. The accidents happening on curves with grades are also studied (Figure 2.3). It can be found that the most vulnerable locations identified in Figure 2.2 (snowy road) are similar to those shown in Figure 2.3 (on grades), which is understandable since both scenarios will create some challenges for the truck drivers to stop efficiently.

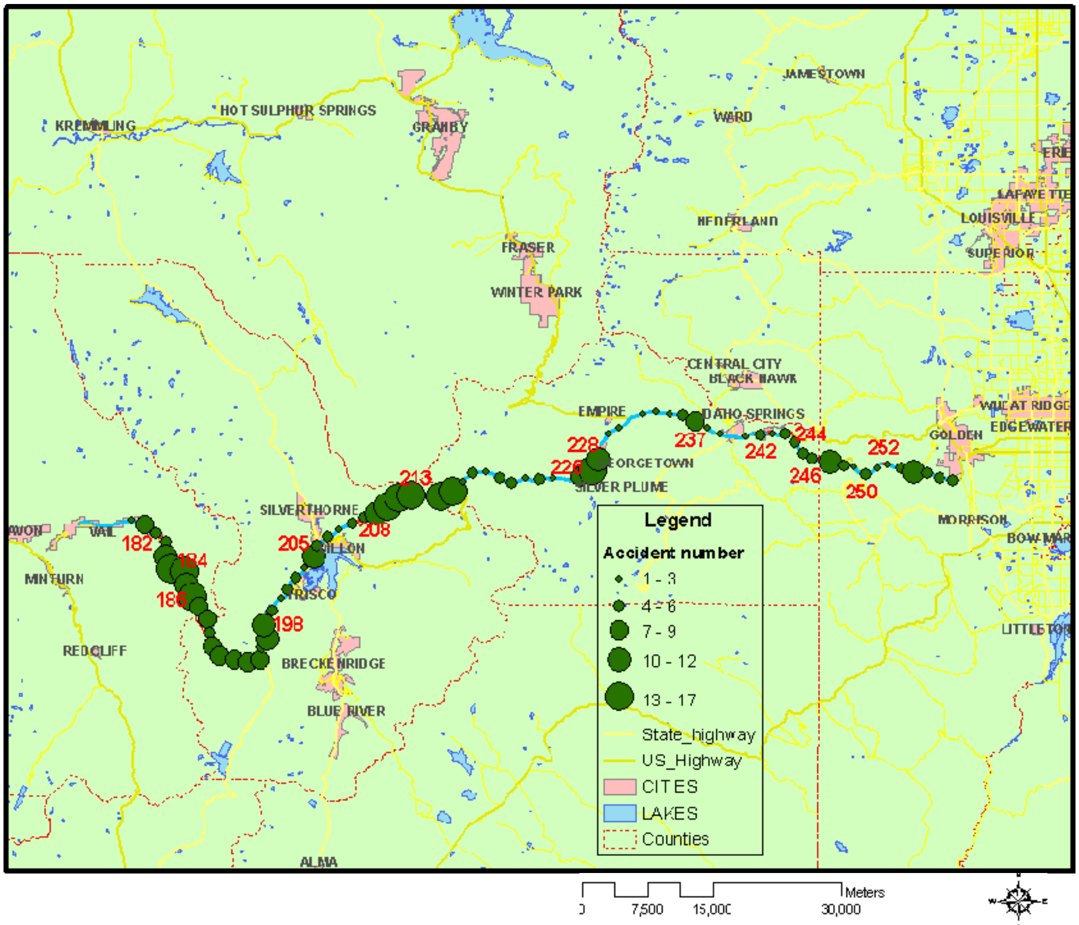


Figure 2.2 Historical accidents on snow-covered road surface (1996-2005)

As shown in Figure 2.3, MP 242-248 suffered from frequent accidents because of the well-known steep grades (6%) that are coupled with sharp curves. Based on the observations from Figure 2.2 and Figure 2.3, it is obvious that both the road surface condition and the road geometric condition (e.g., grade and curves) have large impacts on the accident risk for trucks. The similarities between the observations in Figures 2.2 and 2.3 suggest that two such critical conditions (i.e., road-surface and geometric) work interactively to pose threats to truck safety under adverse driving environments. Because the complex terrain is common throughout the I-70 corridor in Colorado, the historical accidents on snow-covered road surfaces and grade curves were found to occur in nearly all portions of the entire corridor with a comparatively higher number of accidents on the western part.

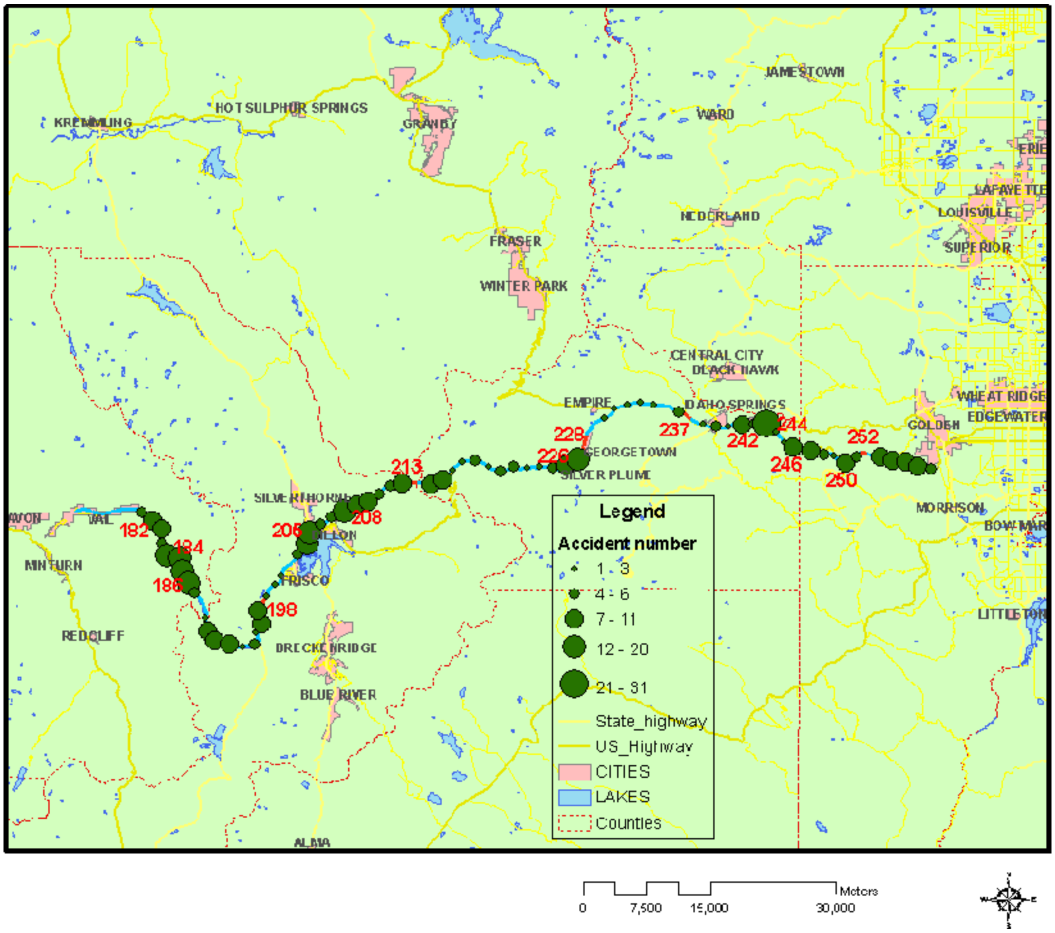


Figure 2.3 Historical accidents on grade curves (1996-2005)

3. DETERMINISTIC VEHICLE ACCIDENT SIMULATION MODEL

To provide essential background information for the reliability-based model, the deterministic accident simulation model will be briefly introduced; more details can be found in reference (Chen and Chen 2010).

3.1 External Forces on Vehicle

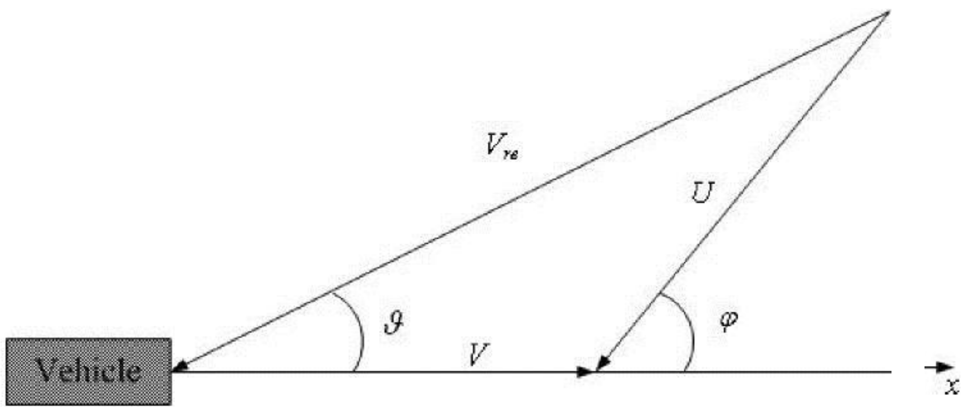


Figure 3.1 Addition of the Velocity Vectors

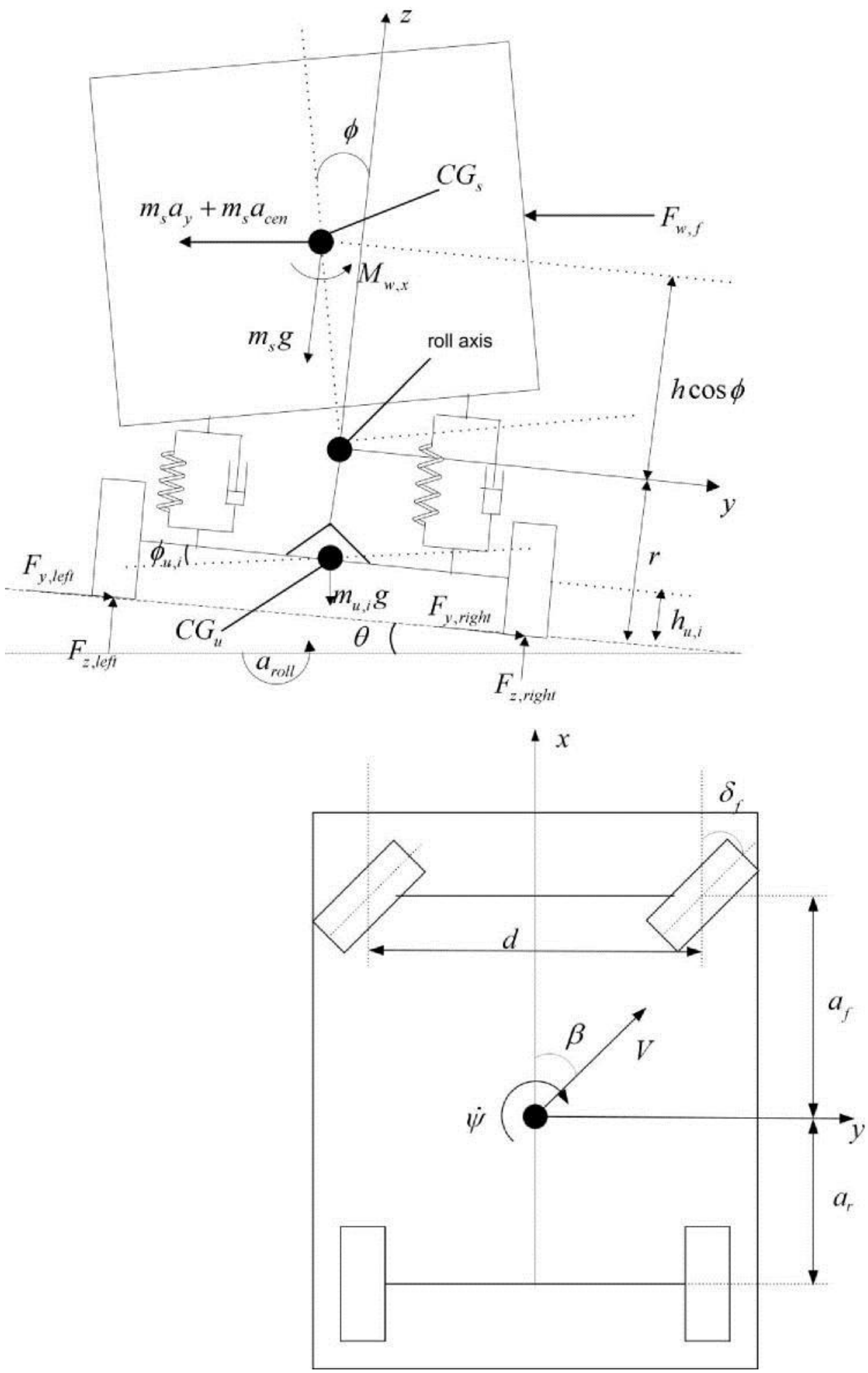


Figure 3.2 Single-body Vehicle Model

The lateral tire forces for the front and rear axles are assumed to be always perpendicular to the direction of the driving velocity of the wheels, which are defined in Equation (3.1) (Gaspar et al. 2004, 2005).

$$F_{y,i} = \mu_{friction} c_i \alpha_i = \mu_{friction} c_i (-\beta + \delta - a_i \cdot \dot{\psi} / V) \quad , i=f \text{ or } r \qquad (3.1)$$

where c_i *(i= f* or *r)* is the tire cornering stiffness and α_i *(i= f* or *r)* is the tire side slip angle associated with the front and the rear axles, respectively. $\mu_{friction}$ is the road friction coefficient. Subscripts *y*, *f*, and *r* denote the lateral direction (*y* direction), front and rear wheels, respectively. β, δ, and $\dot{\psi}$ are the sideslip angle, steer angle and yaw rate, respectively; V is the driving speed of the vehicle and a_i (i=f or r) are the longitudinal distances from the center of sprung mass to the front and the rear axles, respectively.

Quasi-static assumptions are usually applied in order to simulate the wind loads acting on moving vehicles (Baker 1987, 1994, Coleman and Baker 1994). The quasi-static forces and moment induced by crosswind in *x*, *y*, and *z* directions are respectively defined as follows (Baker 1994):

$$F_i = 0.5 \rho C_{Fi} A V_{re}^{\,2} \qquad \text{i=x, y or z} \qquad (3.2)$$

$$M_i = 0.5 \rho C_{Mi} A V_{re}^{\,2} h_{re} \qquad \text{i=x, y or z} \qquad (3.3)$$

where F_i (i=x, y or z) are the drag, lift, and side forces acting on the vehicle, respectively. M_i (i=x, y or z) are the rolling, yawing, and pitching moments acting on the vehicle, respectively. ρ is the density of air. A is the reference area of the vehicle. h_{re} is the reference arm. C_{Fi} (i=x, y or z) are the wind force coefficients and C_{Mi} (i=x, y or z) are the wind moment coefficients in (about) *x*, *y*, and *z* directions, respectively. These wind coefficients are typically obtained from wind tunnel experimental studies with scaled vehicle models (Baker 1994). V_{re} is the relative wind speed to the moving vehicle as shown in Figure 3.1.

3.2 Transient Vehicle Dynamic Models (Chen and Chen 2010)

The sprung mass rotates around the roll center which is dependent on the kinematical properties of the suspensions (Figure 3.2). The unsprung masses can rotate with the vertical compliance of the tires. Five force and moment equilibrium equations of vehicle motions of sprung mass, unsprung masses, and suspensions in *y* and *z* directions are defined in Equations (3.4-3.8).

$$m_s h \ddot{\phi} = mV(\dot{\beta} + \dot{\psi}) - F_{y,f} - F_{y,r} + F_{w,y} - mg\theta + ma_y \qquad (3.4)$$

$$-I_{x'z'} \ddot{\phi} + I_{z'z'} \ddot{\psi} = F_{y,f} a_f + F_{y,r} a_r + M_z \qquad (3.5)$$

$$\begin{aligned} I_{x'x'} \ddot{\phi} - I_{x'z'} \ddot{\psi} &= m_s gh\phi + m_s Vh(\dot{\beta} + \dot{\psi}) + M_x - m_s gh\theta + m_s ga_y + F_{w,y} h_w \\ &\quad - k_f (\phi - \phi_{t,f}) - l_f (\dot{\phi} - \dot{\phi}_{t,f}) + u_f - k_r (\phi - \phi_{t,r}) - l_r (\dot{\phi} - \dot{\phi}_{t,r}) + u_r \end{aligned} \qquad (3.6)$$

$$rF_{y,f} = -m_{u,f}V(h_{u,f} - r)(\dot{\beta} + \dot{\psi}) + m_{u,f}g(h_{u,f} - r)\phi_{t,f} + m_{u,f}g(h_{u,f} - r)\theta - a_{roll}I_{x'x'}m_f / m$$

$$-m_{u,f}a_y(h_{u,f} - r) + k_{t,f}\phi_{t,f} - k_f(\phi - \phi_{t,f}) - l_f(\dot{\phi} - \dot{\phi}_{t,f}) + u_f \tag{3.7}$$

$$rF_{y,r} = -m_{u,r}V(h_{u,r} - r)(\dot{\beta} + \dot{\psi}) + m_{u,r}g(h_{u,r} - r)\phi_{t,r} + m_{u,r}g(h_{u,r} - r)\theta - a_{roll}I_{x'x'}m_r / m$$

$$-m_{u,r}a_y(h_{u,r} - r) + k_{t,r}\phi_{t,r} - k_r(\phi - \phi_{t,r}) - l_r(\dot{\phi} - \dot{\phi}_{t,r}) + u_r \tag{3.8}$$

where the subscripts r and f refer to the rear and front axles, respectively. $F_{w,y}, M_x, M_z$ are lateral wind force, wind-induced roll moment, and wind-induced yaw moment, respectively. θ is road superelevation. a_y and a_{roll} are accelerations in *y* direction and rolling direction of the supporting infrastructures (e.g., pavement or bridge), respectively. m, m_s, m_u are total mass, sprung mass, and unsprung mass, respectively. h is the height of the center of sprung mass, measured upwards from the roll center. r and h_u are the heights of rolling center and unsprung mass center, measured upwards from ground surface, respectively. $F_{y,f}$ and $F_{y,r}$ are lateral forces of front and rear tires, respectively. $I_{x'x'}$, $I_{x'z'}$, $I_{z'z'}$ are roll moment, yaw-roll product, and yaw moment of inertia of sprung mass, respectively. k, k_t, l are roll stiffness of suspension, roll stiffness of tire, and roll damping rate of suspension, respectively. ϕ and ϕ_t are absolute roll angle of sprung mass and unsprung mass, respectively. β and ψ are sideslip angle and heading angle. u is active roll torque.

The dynamic equations as shown above will be updated after wheels have been lifted up or have started to sideslip. The corresponding set of transient dynamic equations will be automatically selected to continue the simulations when the particular criteria are satisfied (Chen and Chen 2010). It is noted that driver behavior is not considered in the dynamic equations because of the lack of a well-accepted model from existing literature that can accurately relate the steering angle and the dynamic motion of vehicles (Chen and Chen 2010). For the purpose of brevity, details of other transient equation sets after wheels are lifted up or start to sideslip are not repeated here. More information about the dynamic models can be found in Chen and Chen (2010).

By solving a series of transient dynamic equations and checking against the accident criteria at each time step, the deterministic simulation can be continued. The whole simulation repeats by gradually increasing the driving speed. The highest allowable driving speed without causing any type of accident under a specific combination of environmental and vehicular conditions is called the critical driving speed (CDS) (Chen and Chen 2010).

4. RELIABILITY-BASED VEHICLE SAFETY ASSESSMENT MODEL (CHEN AND CHEN 2011)

4.1 Limit State Function

Taking the summation of moment about the point on the ground plane at the mid-track position, the weight transfer ratio W_{trans} between the left and right wheels can be derived as (Sampson 2000):

$$W_{trans} = ((mV(\dot{\beta} + \dot{\psi}) + ma_y + mg(\phi - \theta)) \times h_{cm} + F_{w,y}(h_w + r) + M_x + a_{roll} I_{x'x'}) / d \quad (4.1)$$

where h_{cm} is the height of center of mass for the whole truck, d is the track width, and h_w is the height of lateral wind load $F_{w,y}$ measured upwards from the roll center.

It is known that a vehicle may or may not actually roll over when the wheels are lifted up. The existing studies (Chen and Chen 2010) showed that in most scenarios, rollover accidents occur after wheels are lifted up. Only in a few special cases the truck may not actually roll,over after wheels are lifted up. In order to capture more general scenarios of rollover, the criterion of wheels being lifted up is selected in the present study to develop the limit state function $g_{\lim}$ for rollover accidents:

$$g_{\lim} = mg/2 - F_{w,z}/2 - W_{trans} \quad (4.2)$$

where W_{trans} is the weight transfer ratio as defined in Equation (4.1), $F_{w,z}$ is the wind-induced lift force.

For sideslip accidents, the limit state function $g_{\lim}$ is developed based on the criterion that the summation of the actual lateral friction forces of all wheels equals to the maximum allowable lateral friction forces for the particular road surface. Accordingly, the limit state function $g_{\lim}$ for sideslip can be developed in Equation (4.3):

$$g_{\lim} = F_{la,f}^{\max} + F_{la,r}^{\max} - \left(F_{y,f} + F_{y,r}\right) = \mu_{friction}\left(F_{z,f} + F_{z,r}\right) - \left(F_{y,f} + F_{y,r}\right) \quad (4.3)$$

where $F_{z,f}$ and $F_{z,r}$ are the vertical forces on the front and rear axles, respectively. $F_{la,f}^{\max}$ and $F_{la,r}^{\max}$ are the maximally allowable lateral friction forces of the front and the rear wheels for a given road surface condition, respectively. $\mu_{friction}$ is the road friction coefficient. The effect of acceleration or deceleration on tire friction force is not considered in the equation.

Because $F_{y,f}$, $F_{y,r}$ in Eq. (4.3) as well as W_{trans} in Eq. (4.2) can only be quantified after solving coupled dynamic equations [e.g., Equations (3.4-3.8)], the limit state functions as shown in Equations (4.2) and (4.3) cannot be expressed as explicit functions like the case when the rigid-body vehicle model was used in some existing studies (Sigbjornsson and Snaebjornsson 1998; Snaebjornsson et al. 2007). Under any combination of driving conditions, continuous simulations with the deterministic model will be conducted until whichever of the two accident types occurs first or the simulation results converge (i.e., no accident occurs). The corresponding limit state function for the particular accident type will be used to continue the reliability analysis.

4.2 Response Surface Method

Monte Carlo simulation is an accurate, robust, and easy-to-use method for the reliability analysis of structures with implicit limit state functions (Bucher and Bourgund 1990). The associated enormously large amount of computation time, however, often makes the application of Monte Carlo simulation on some complicated problems, like the vehicle dynamic simulations as introduced above, cost-prohibitive. Response surface method (Bucher and Bourgund 1990, Rajashekhar and Ellingwood 1993) is a popular approach to approximate the originally complex and implicit limit state functions by a simple response surface function. In the present study, the Response Surface Method (RSM) is adopted here to predict the reliability index under adverse driving conditions. Because different advanced reliability analytical approaches have their respective advantages, it is noted that the RSM approach may not necessarily be the only or the best reliability method for this particular problem. An investigation of other advanced approaches and the comparison deserve a separate study in the future.

A second-order polynomial without cross terms will be used in the present study (Bucher and Bourgund 1990):

$$\hat{g}(X) = a_0 + \sum_{i=1}^{k} a_i X_i + \sum_{i=1}^{k} a_{ii} X_i^2 \qquad (4.4)$$

where $\hat{g}(X)$ is the approximate limit state function of Equation (4.2) or Equation (4.3). X_i (i=1,2,…,k) is the i^{th} random variable. k is the total number of random variables. a_0, a_i, a_{ii} are coefficients to be determined by solving a set of simultaneous equations. As a result, the total number of unknown coefficients of Equation (4.4) is 2k+1.

The random variable X_i in Equation (4.4) can be defined as (Bucher and Bourgund 1990; Rajashekhar and Ellingwood 1993)

$$X_i = \mu_i \pm h_i \sigma_i \qquad (4.5)$$

where h_i is an arbitrary factor. μ_i and σ_i are the mean and the standard deviation of X_i, respectively.

In the present study, the initial value of h_i is assumed to be a typical value of 3.0 for the first iteration and 1 for the subsequent iterations (Rajashekhar and Ellingwood 1993). The initial center point is chosen by setting all the random valuables as their respective mean values. The iterative linear interpolation scheme of RSM suggested by Rajashekhar and Ellingwood (1993) is used in this study.

4.3 Safety Index of Vehicle

After the limit state functions have been approximated using RSM, first order reliability method (FORM) is applied to predict the failure probability and safety index (Haldar and Mahadevan 2000). The typical FORM method has been utilized by many previous studies (Haldar and Mahadevan 2000). The corresponding limit state probability (accident probability) $p_{failure}$ can be estimated by the following equation (Haldar and Mahadevan 2000):

$$p_{failure} = \Phi(-\beta) \qquad (4.6)$$

in which $\Phi(\ )$ is the standard normal probability distribution function. β is the reliability index, which will be referred as safety index in the following numerical study.

4.4 Numerical Study

With the reliability-based analytical model illustrated above, a numerical example of assessing truck safety is conducted in the following. Random variables are selected and defined to capture the associated uncertainties.

Depending on the degree of uncertainty and the relative significance to the accident risk prediction results, all the parameters in the analytical model as introduced in Section 3 can be treated as either random variables or deterministic parameters. Based on the findings from the parametric studies of the deterministic model (Chen and Chen 2010) as well as other existing studies (Snaebjornsson et al. 2007), the random variables selected in this study include wind velocity, wind direction, vehicle speed, frictional coefficients, steering angle, vehicle sprung mass and the height of the center of the sprung mass. Similar to the existing studies on describing the uncertainties of variables (Snaebjornsson et al. 2007), most basic random variables are assumed to have a normal distribution, except that the friction coefficient has the truncated normal distribution. The full list of random variables as well as their distributions is given in Table 4.1. The values for other deterministic parameters of vehicles and environments will be introduced throughout the example and the details can be found in reference (Chen and Chen 2010).

Table 4.1 Statistics of the Random Variables for the Simulation

Variable	Notation	Distribution	Standard deviation (σ)	Source
Road friction coefficient	$\mu_{friction}$	Truncated normal	0.05	Snaebjornsson et al. (2007)
Vehicle driving velocity (km/h)	V	Normal	0.15 μ_V	Snaebjornsson et al. (2007)
Steer angle ($^\circ$)	δ	Normal	0.2 μ_δ	Assumed
Wind speed (m/s)	U	Normal	2	Snaebjornsson et al. (2007)
Wind direction ($^\circ$)	φ	Normal	7.5	Snaebjornsson et al. (2007)
Vehicle sprung mass (kg)	m_s	Normal	0.1 μ_{m_s}	Assumed
Height of center of sprung mass (m)	h	Normal	0.1 μ_h	Assumed
Bridge accelerations in lateral direction (g)	a_y	Normal	0.2 μ_{a_y}	Assumed
Bridge accelerations in rolling direction (rad/s^2)	a_{roll}	Normal	0.2 $\mu_{a_{roll}}$	Assumed

Note: μ() is the mean value of the random variable.

5. GIS-BASED ADVISORY DRIVING INFORMATION SYSTEM

5.1 GIS-based System

Utilizing ArcGIS software and Matlab software, a GIS-based advisory driving information system has been generated to report all the analytical data and results on the GIS map with topographic conditions embedded. By displaying the data on a GIS-based map, different accident risk indices can be easily displayed and compared on the GIS map. As a result, the information will be helpful for transportation management agencies or trucking companies to plan the trip, manage the fleet, and educate novice drivers and people who plan to drive the studied highway about safe driving.

Figure 5.1 shows the critical steps for generating the GIS-based map. Users utilize the dialogue box shown in Figure 5.2 to input wind speed file and define the road condition. In the future, wind data can also be generated automatically using weather station data or other data. Other information like curving radius and road grade are saved in the ArcGIS database in advance. Users can adopt the current speed limit default, or define different driving speeds for each location by importing a user-defined speed file. As shown in Figure 5.2, four different road conditions can be chosen: dry, wet, snowy, and icy. Users import the wind speed document by choosing the document location. Users can also import the speed limit document if they don't want to use the current speed limit. Figure 5.3 shows the wind speed Excel document example; wind data can be also save in Access and other documents.

After users finish inputting the necessary information, ArcGIS automatically generates the database, which is useful for Matlab analysis. The system developers have defined the database format using VB programming, so ArcGIS can collect the information to generate the database. Figure 5.4 shows the example feature class of the generated database. For example, the data of each line show the information for each milepost: speed limit, friction coefficient, wind speed, curving radius, and road grade. Some of the feature classes are from the ArcGIS database: milepost speed_limit, radius, and grade. Others are defined by users: wind_speed and friction coefficient.

Using the Dynamic Data Exchange (DDE) method, ArcGIS sends the database to Matlab, which then can adopt the analyst models to calculate the analytical data, such as safety index, traffic efficiency, and so on. Then using the DDE method, Matlab sends the results back to ArcGIS. ArcGIS generates the new database, which saves the traffic safety and efficiency information based on the Matlab analysis. Figure 5.5 shows the example of the updated database. Two new columns have been added, index_safe and prob_acc, which mean safety index and probability of accident.

Using VB programming, ArcGIS can generate a GIS-based map according to related database. Utilizing the updated database from the Matlab analysis, GIS-based maps are then automatically generated. Finally, ArcGIS exports the GIS map automatically, in PDF or other format. Figures 5.6-5.9 show some examples or the GIS map. For examples, Figures 5.6-5.7 show the safety index of several mileposts on I-70 and Figures 5.8-5.9 show the accident probability of these mileposts. The road condition and wind speed were defined previously in Figures 5.2 and Fig. 5.3. The definition of safety index and accident probability is defined in Section 4. According to Equation (4.6), the corresponding accident probability is about 50% if the safety index is equal to 0. And if the reliability index is 3, the accident probability is 0.13%. By using VB programming and the DDE method, after the user defines all road and weather conditions, ArcGIS and Matlab can automatically do steps 2-6. VB programming is done before the users defined all the environmental conditions by the system developer, so ArcGIS can do all the steps automatically; for example, updating the database or generating the GIS-based map automatically after the users defined the conditions. In the future, road and weather conditions can be received on an Internet server, such as a weather station database. The user can then check the real-time GIS-based advisory driving information system on a website. Users simply need to choose certain highway and time sections, and GIS-based advisory driving information system can automatically generate a GIS-based map with safety information after the system analyzes all the related information obtained from the database. In the future, based on the previous work, a GIS-based advisory driving information website can be generated using ArcGIS server programming.

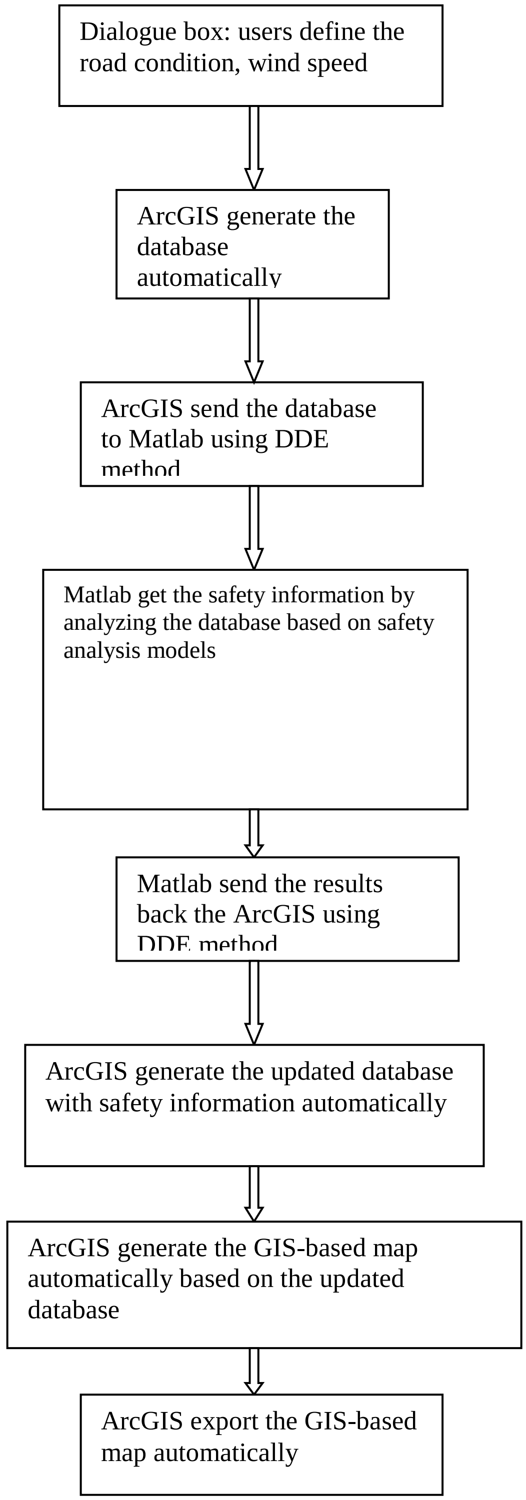


Figure 5.1 Flow Map of the GIS-based Advisory Driving Information System

5.2 Advisory Speed with Certain Accident Probability

For any given hazardous condition and any specific vehicle, the occurrence of single-vehicle accidents is significantly related to excessive driving speeds. To maintain an appropriate driving speed in order to balance safety and efficiency is obviously critical. Therefore, the advisory driving speed is the highest allowable driving speed, which results in the crash risk being at the desired level in a reliability-based model.

Based on the GIS-based advisory driving information system, we can get the safety index or accident probability of certain highway sections under the current speed limit. Also, we can get an advisory speed with a certain accident probability. For instance, if we know there is a windstorm on I-70, the accident probability is obviously high when driving according to the current speed limit. So in our study, we would like to know the advisory speed with a certain accident probability like 0.001. The GIS-based advisory driving information system can also get such information. The steps are the same as with calculating the safety index or accident probability. The Matlab analysis model is different, because now the input variables are environmental conditions and a certain accident probability (like 0.001), and the output results are the advisory speeds. If the output is safety index or accident probability, the input variables are environmental conditions and speed limit. Figures 5.10-5.15 show the advisory speed GIS maps under several different conditions. In all those maps, only if the advisory speed is lower than the current speed limit will the advisory speed and milepost information be shown on the GIS map. Figures 5.10-5.11 show the GIS map when the road condition is dry and wind speed is 20 m/s. Figures 5.12-5.13 show the GIS map when the road condition is snowy and wind speed is 10 m/s. Figures 5.14-5.15 show the GIS map when the road condition is icy and wind speed is 10 m/s. For example, Figures 5.10-5.11 indicate that truck drivers should drive much slower than the speed limit on 10 of 15 I-70 sections when the wind speed is 20 m/s. Or transportation management agencies should consider closing some of the I-70 sections (milepost 205, 208 and 213) when the road is icy and wind speed is 10m/s. These GIS-based advisory speed maps will be helpful for transportation management agencies or trucking companies to plan the trip, manage the fleet, and educate novice drivers and people who plan to drive the studied highway about safe driving.

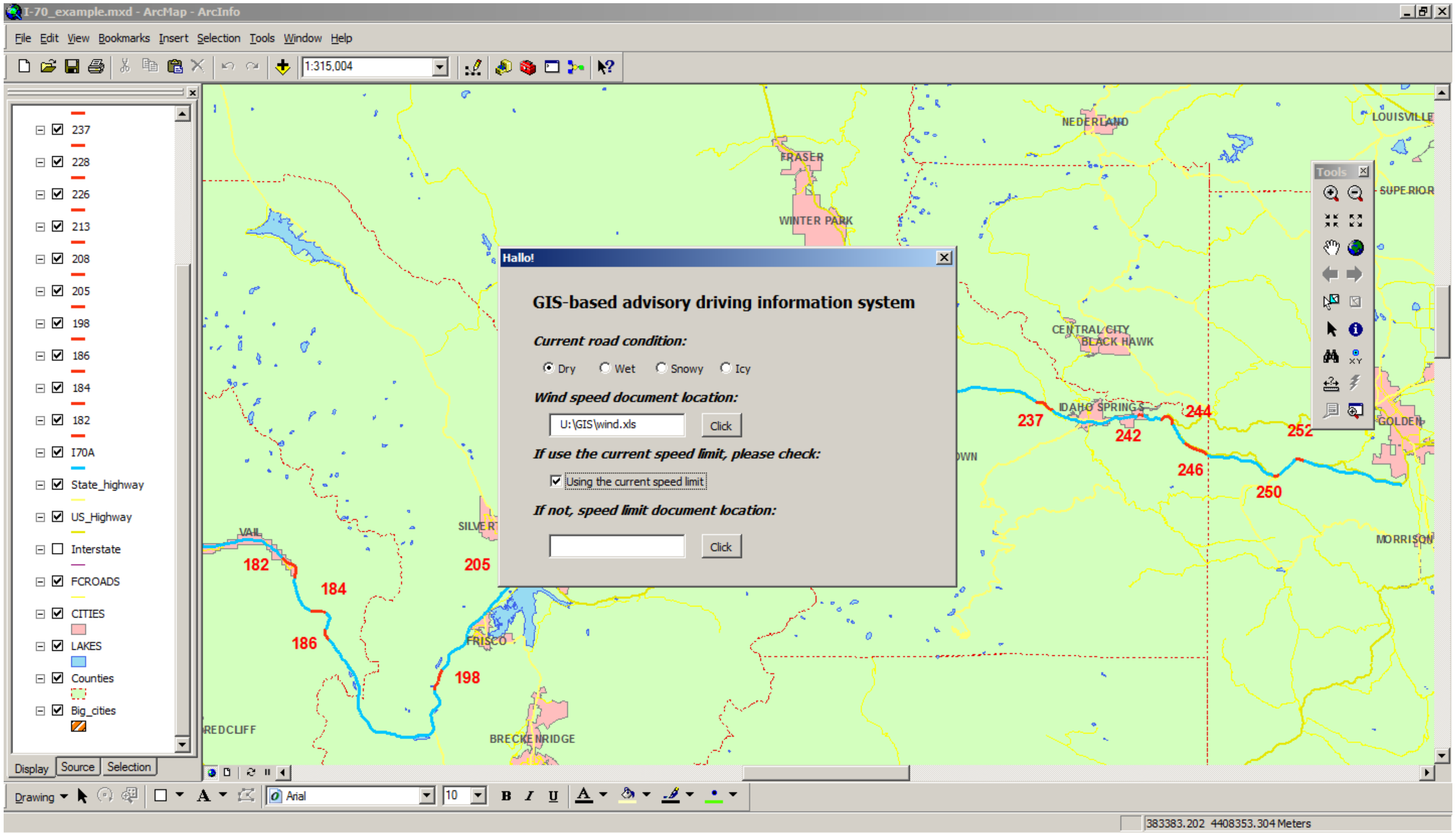
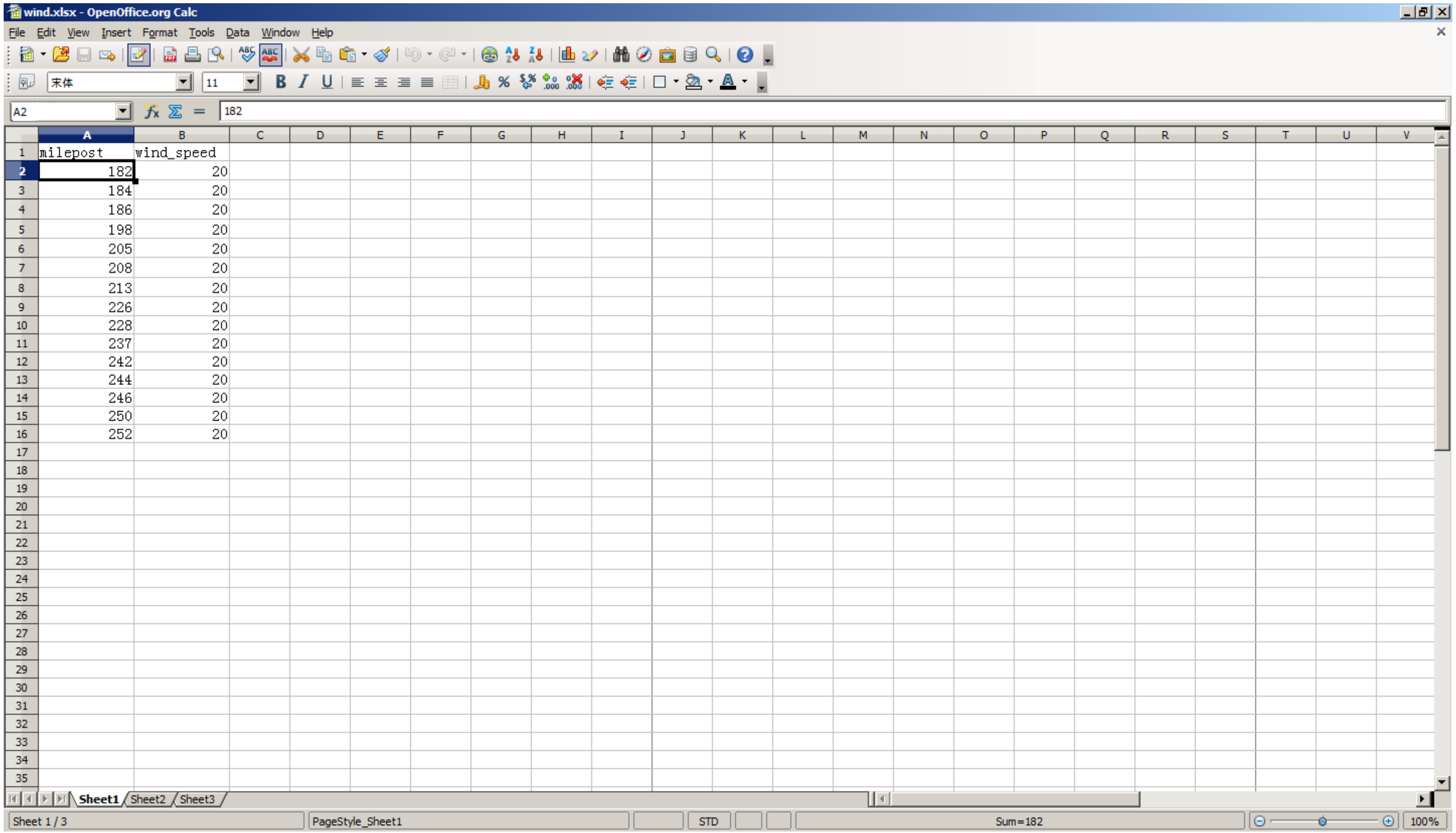
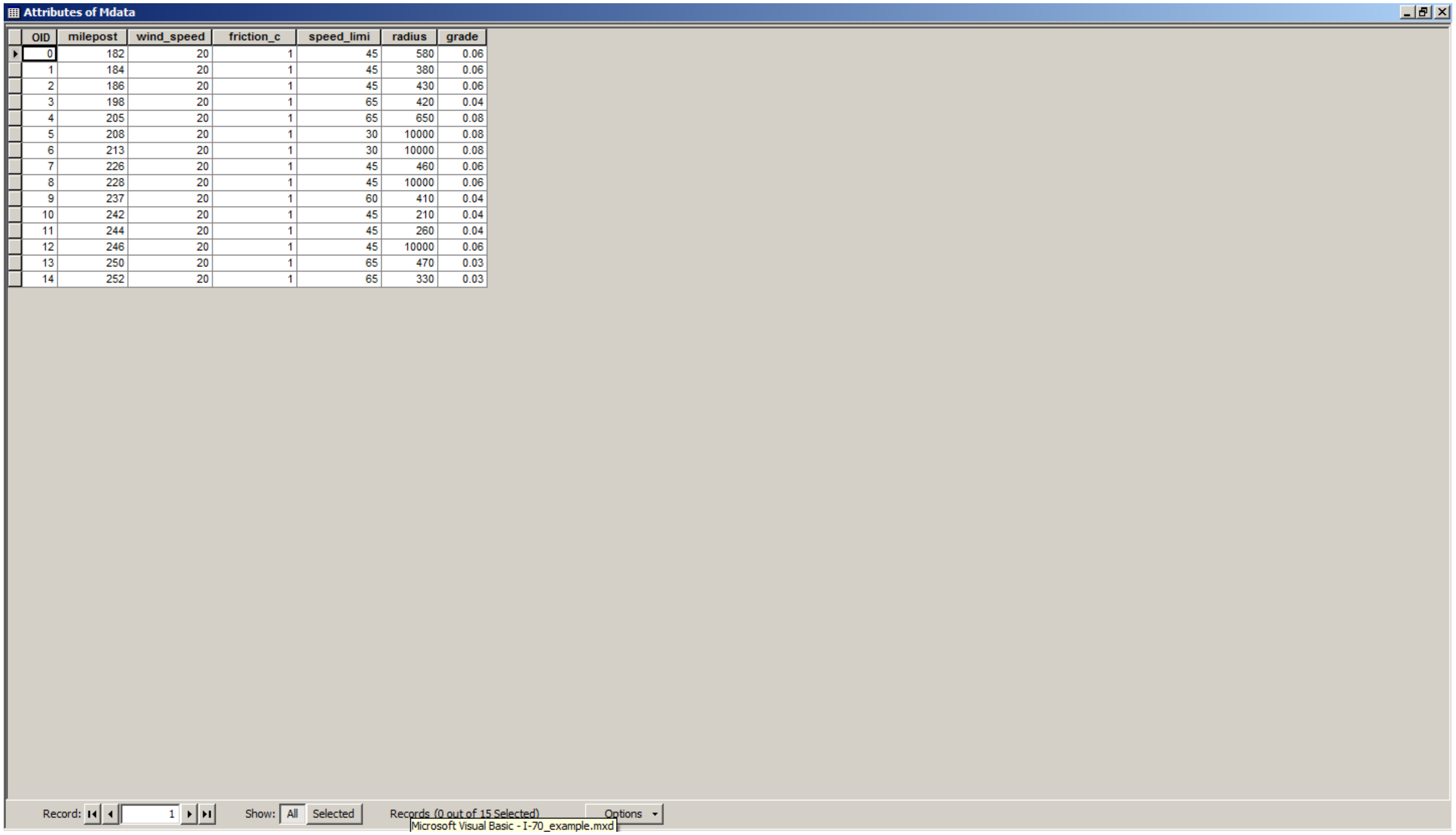


Figure 5.2 Dialogue Box for GIS-based Advisory Driving Information System



milepost	wind_speed
182	20
184	20
186	20
198	20
205	20
208	20
213	20
226	20
228	20
237	20
242	20
244	20
246	20
250	20
252	20

Figure 5.3 Wind Speed Data File Example



Attributes of Mdata

OID	milepost	wind_speed	friction_c	speed_limi	radius	grade
0	182	20	1	45	580	0.06
1	184	20	1	45	380	0.06
2	186	20	1	45	430	0.06
3	198	20	1	65	420	0.04
4	205	20	1	65	650	0.08
5	208	20	1	30	10000	0.08
6	213	20	1	30	10000	0.08
7	226	20	1	45	460	0.06
8	228	20	1	45	10000	0.06
9	237	20	1	60	410	0.04
10	242	20	1	45	210	0.04
11	244	20	1	45	260	0.04
12	246	20	1	45	10000	0.06
13	250	20	1	65	470	0.03
14	252	20	1	65	330	0.03

Record: 1 Show: All Selected Records (0 out of 15 Selected) Options

Microsoft Visual Basic - I-70_example.mxd

Figure 5.4 Form Derived by ArcGIS

Attributes of Fdata

OID	milepost	wind_speed	friction_c	speed_limi	radius	grade	index_safe	prob_acc
0	182	20	1	45	580	0.06	2.9	0.002
1	184	20	1	45	380	0.06	2.5	0.006
2	186	20	1	45	430	0.06	2.7	0.003
3	198	20	1	65	420	0.04	1.3	0.097
4	205	20	1	65	650	0.08	1.7	0.045
5	208	20	1	30	10000	0.08	5.2	0
6	213	20	1	30	10000	0.08	5.2	0
7	226	20	1	45	460	0.06	2.8	0.003
8	228	20	1	45	10000	0.06	3.1	0.001
9	237	20	1	60	410	0.04	1.5	0.067
10	242	20	1	45	210	0.04	1.7	0.045
11	244	20	1	45	260	0.04	2.1	0.018
12	246	20	1	45	10000	0.06	3.1	0.001
13	250	20	1	65	470	0.03	1.5	0.067
14	252	20	1	65	330	0.03	1.1	0.136

Record: 1 Show: All Selected Records (0 out of 15 Selected) Options

Figure 5.5 Form after Matlab Transfer the Results to ArcGIS

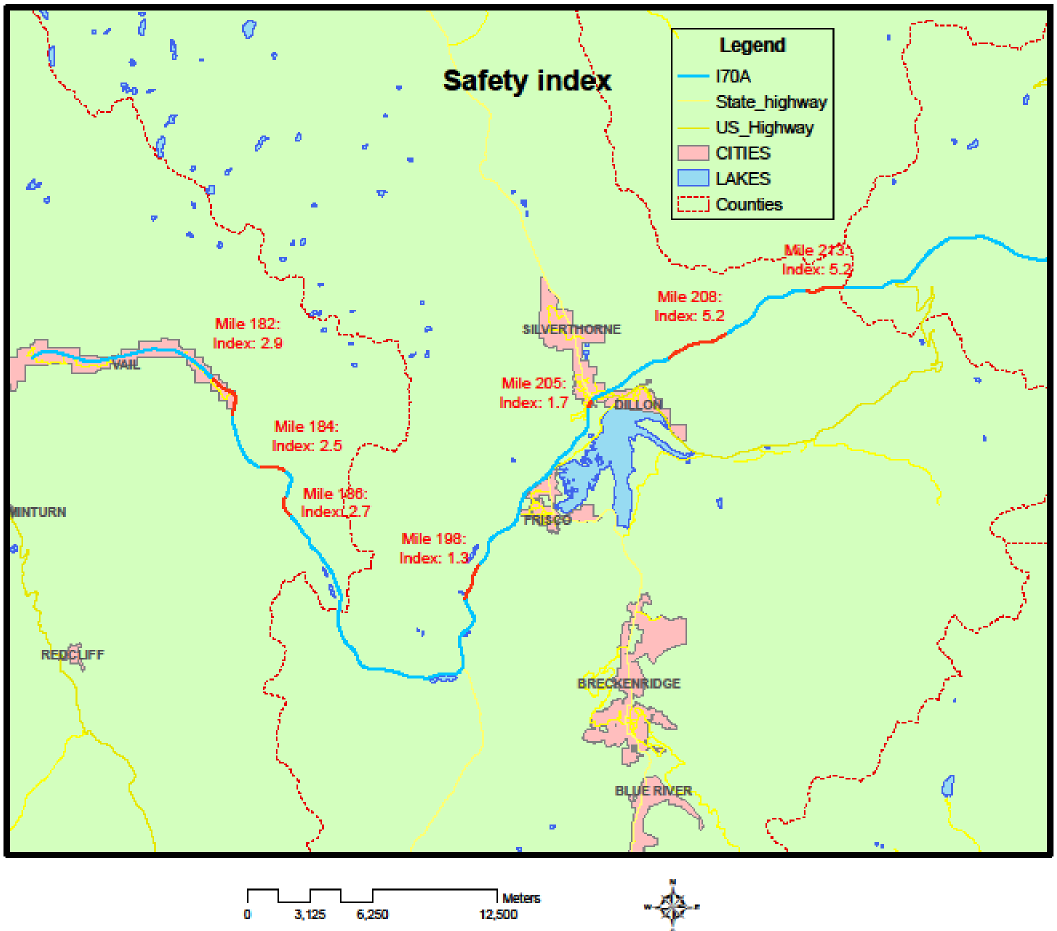


Figure 5.6 Safety Index GIS Map 1

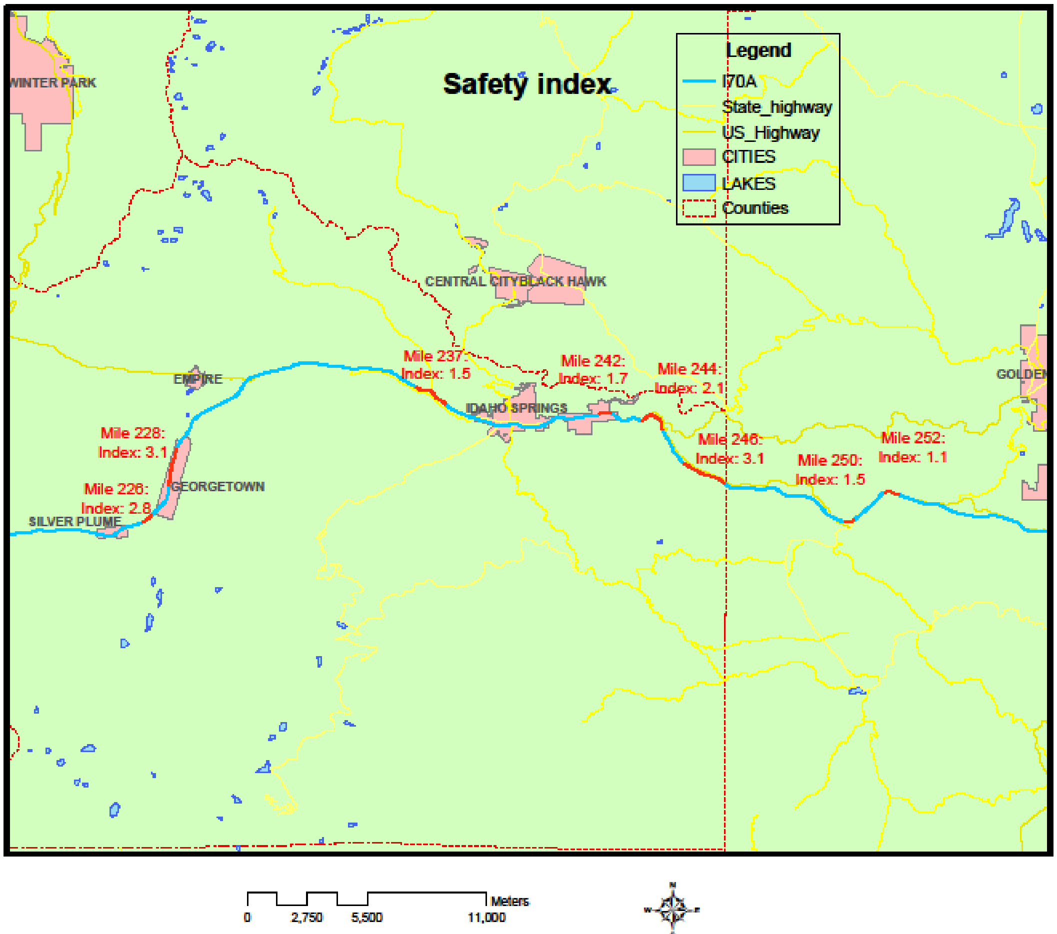


Figure 5.7 Safety Index GIS Map 2

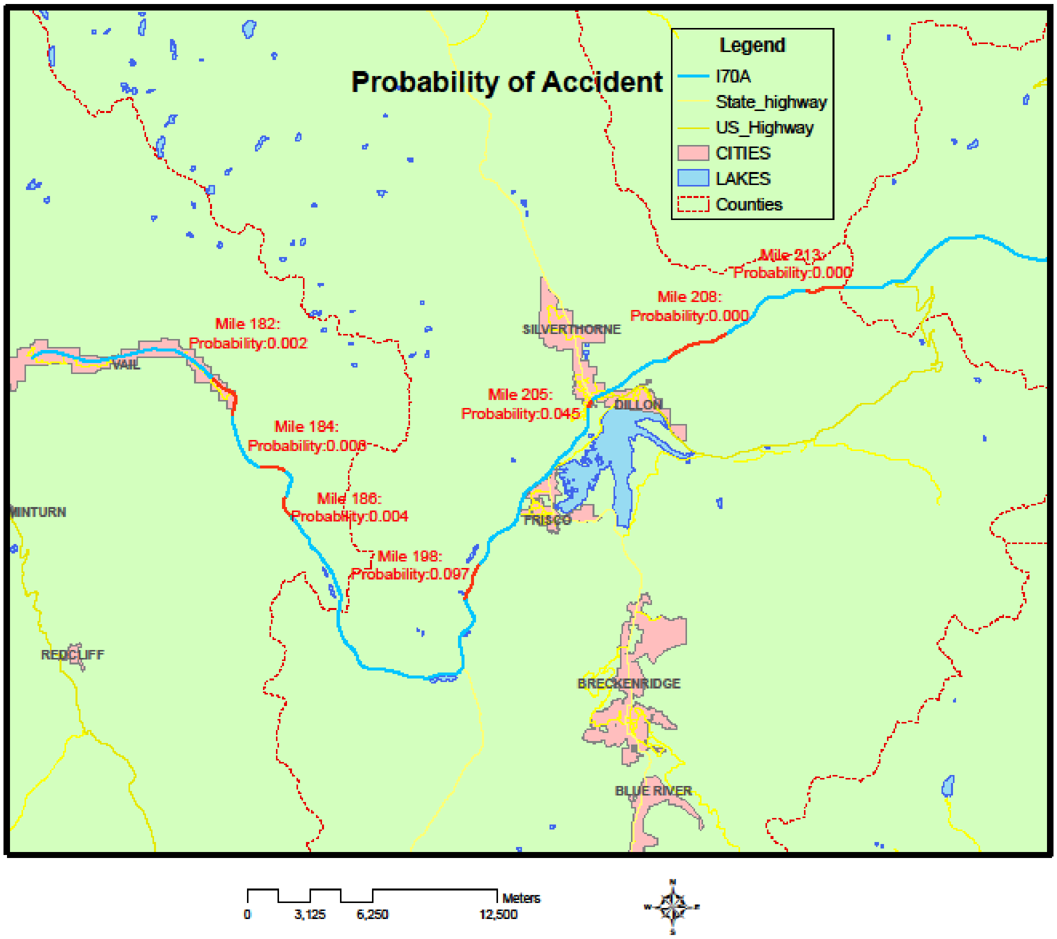


Figure 5.8 Probability of Accident GIS Map 1

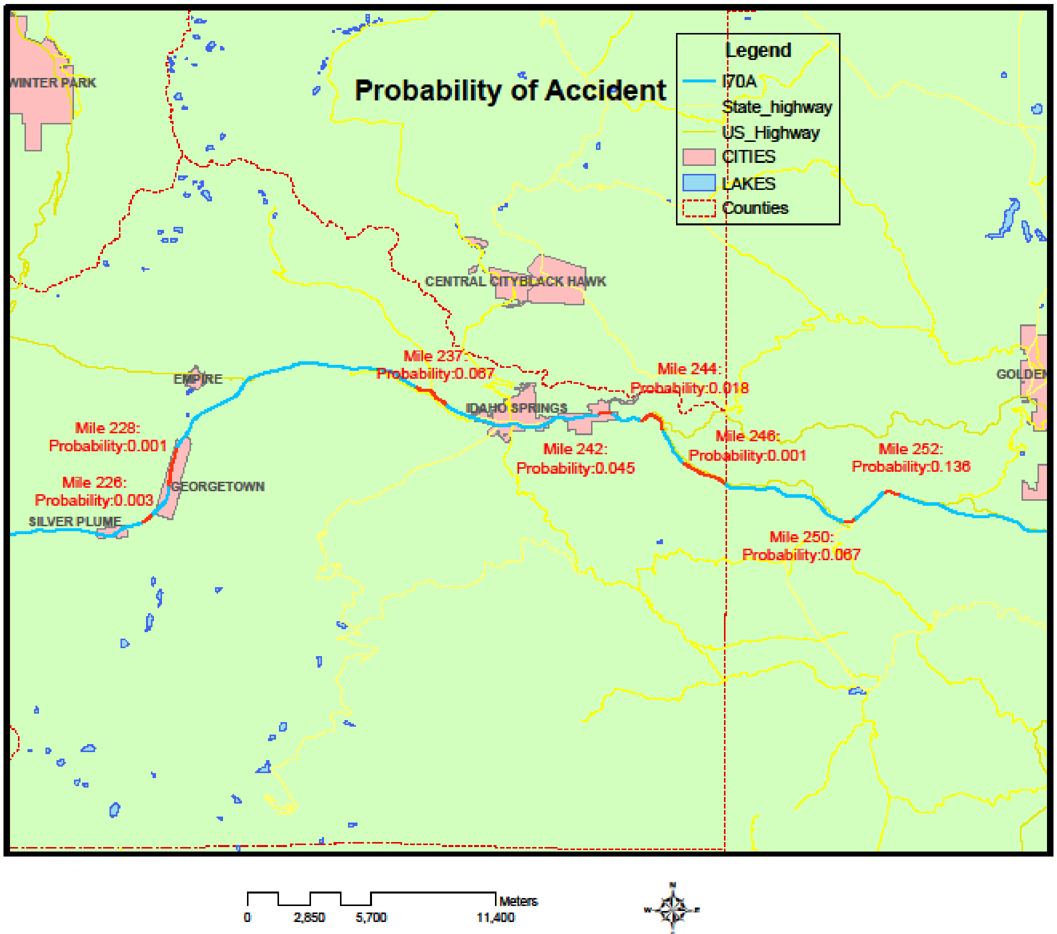


Figure 5.9 Probability of Accident GIS Map 2

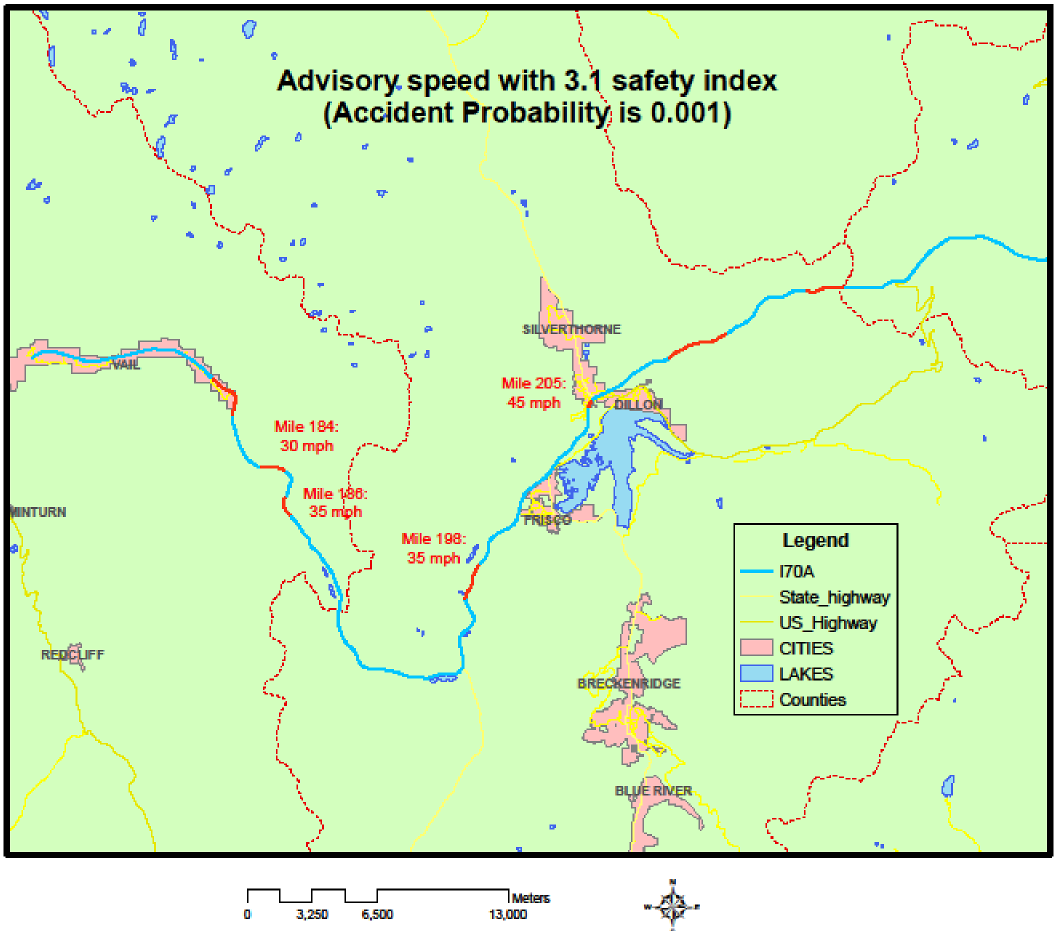


Figure 5.10 Advisory Speed GIS Map 1 (road condition is dry and wind speed is 20 m/s)

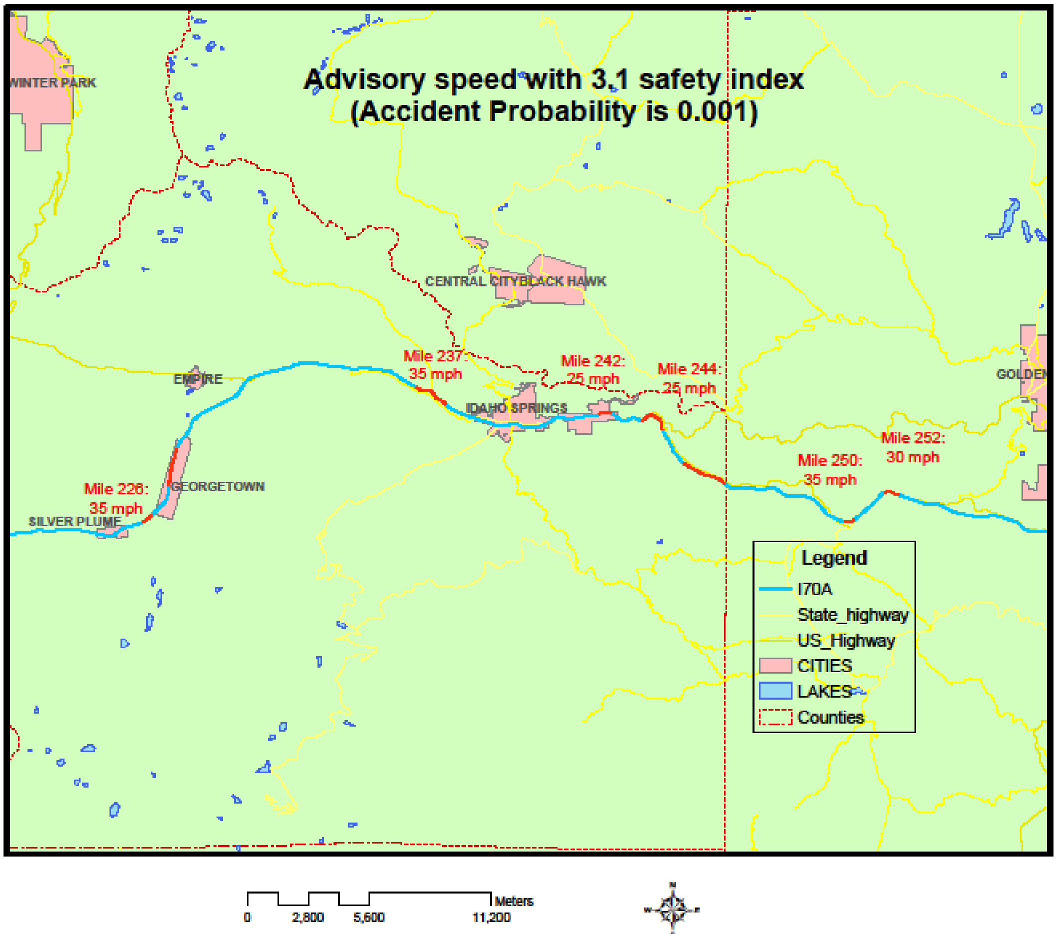


Figure 5.11 Advisory Speed GIS Map 2 (road condition is dry and wind speed is 20 m/s)

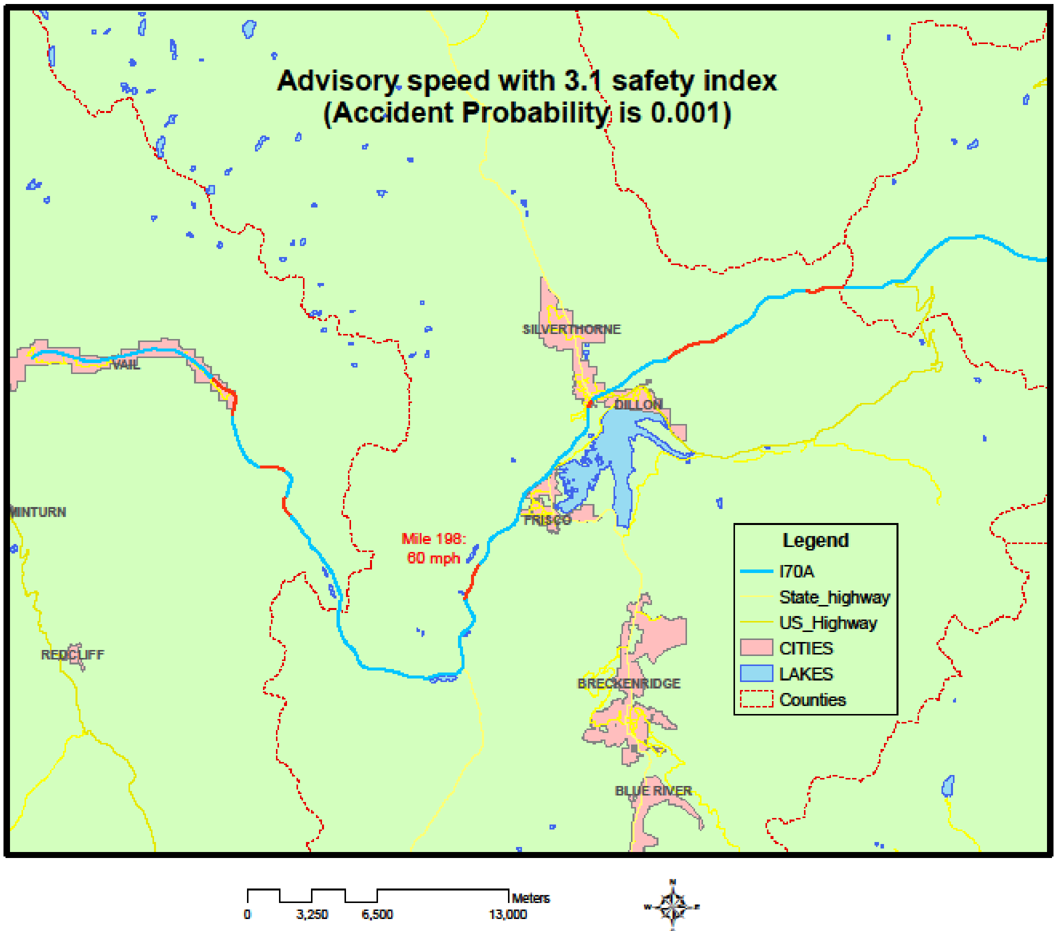


Figure 5.12 Advisory Speed GIS Map 1 (road condition is snowy and wind speed is 10 m/s)

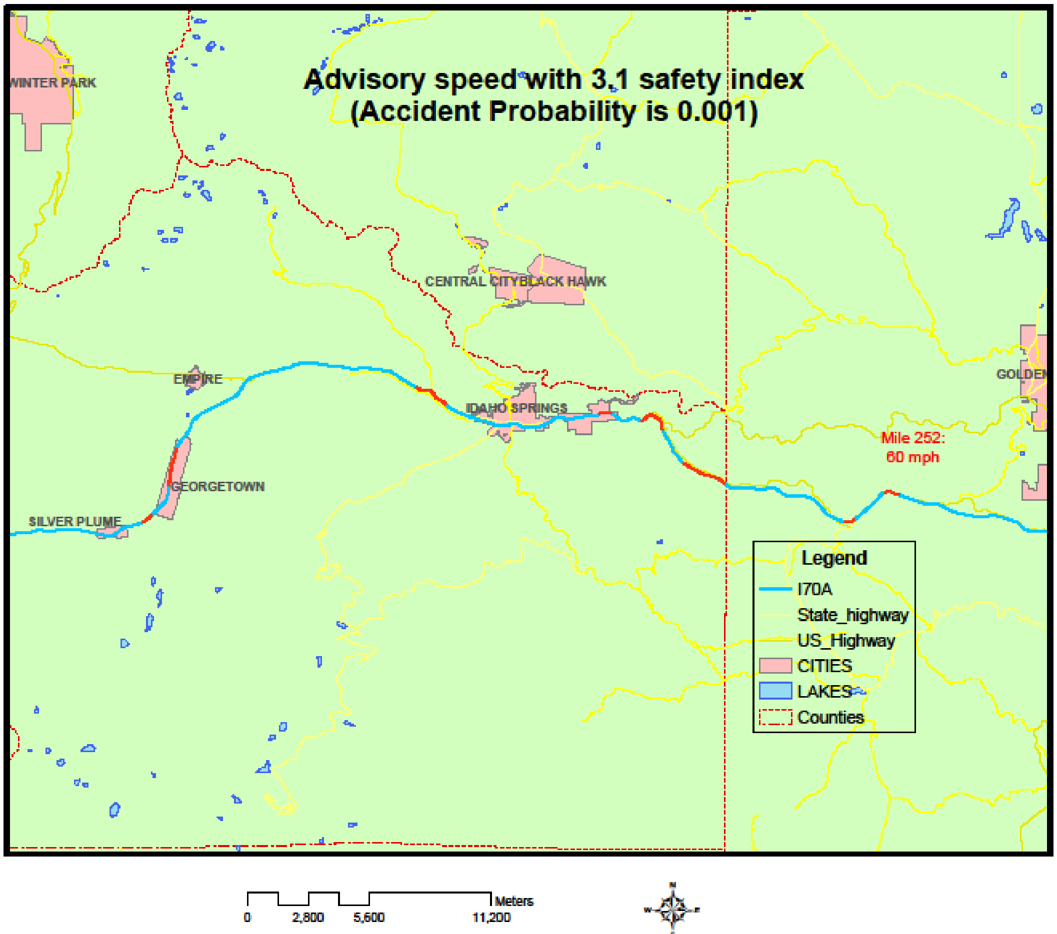


Figure 5.13 Advisory Speed GIS Map 2 (road condition is snowy and wind speed is 10 m/s)

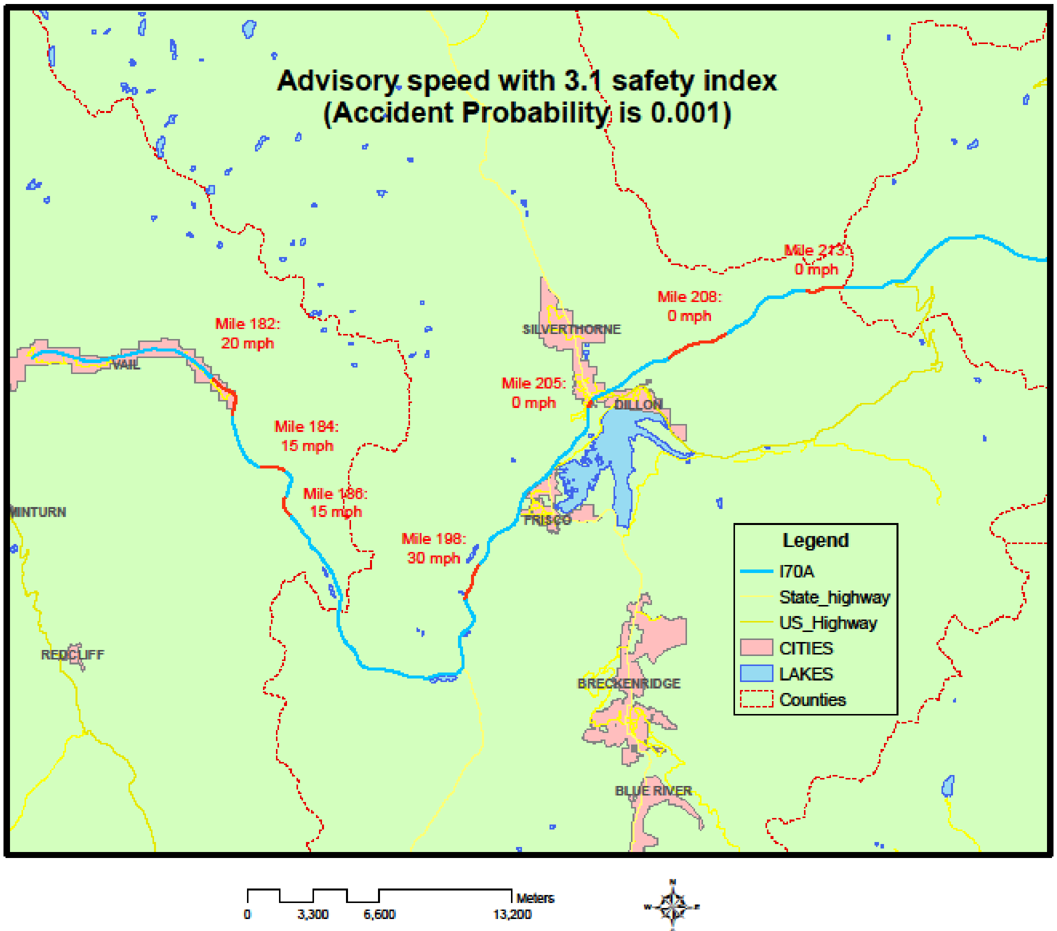


Figure 5.14 Advisory Speed GIS Map 1 (road condition is icy and wind speed is 10 m/s)

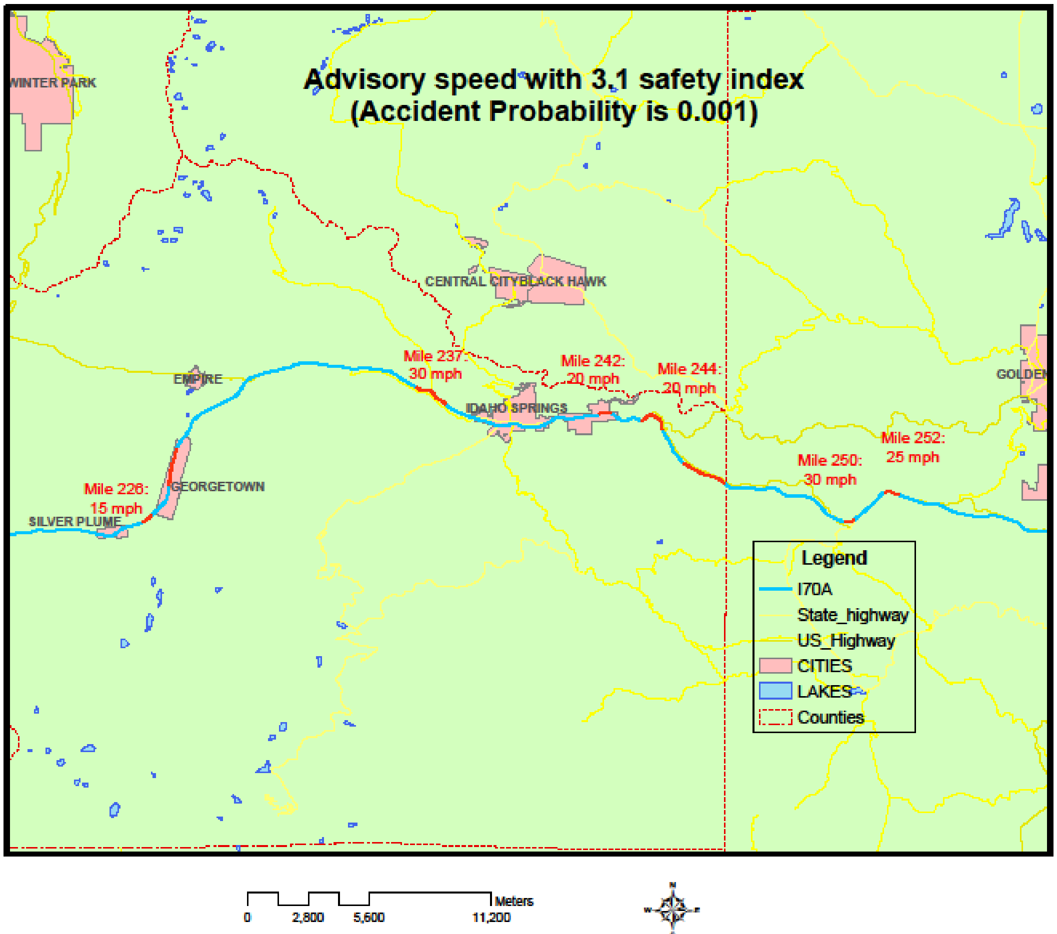


Figure 5.15 Advisory Speed GIS Map 1 (road condition is icy and wind speed is 10 m/s)

6. COST OF TRUCK-RELATED ACCIDENTS

In 2000, the average cost of crashes involving large trucks with a gross weight rating of more than 10,000 pounds was $59,153 (Zaloshnja and Miller, 2004). Multiple combination trucks had the highest cost per crash ($88,483). These costs included medical and emergency services, property damage, lost productivity, and monetary valuation for pain, suffering, and quality-of-life losses associated with these crashes. And these costs rose to $164,730 for large trucks for crashes with injuries. The crash costs per 1,000 truck miles were $157 for single-unit trucks, $131 for single combination trucks, and $63 for multiple combinations.

As a result, information about accident probability and accident cost will be helpful for transportation management agencies or trucking companies to plan the trip, manage the fleet, and educate novice drivers and people who plan to drive the studied highway about safe driving.

7. CONCLUSIONS AND RECOMMENDATIONS

An integrated study was conducted to evaluate the traffic safety of large trucks. A framework of a reliability-based assessment model of vehicle safety under adverse driving conditions was developed. Such a framework is built based on the advanced transient dynamic vehicle simulation models, which can consider the coupling effects between vehicles and adverse driving conditions, such as wind gust, snow-covered or icy road surfaces and/or curving. The single-vehicle safety index is introduced to provide a rational assessment of accident risks by considering the uncertainties of critical variables. Such a methodology, integrating historical accident data analysis and simulation-based traffic safety models, can be used on any mountainous highway with complex driving conditions and high traffic volumes. The I-70 corridor in Colorado was chosen to demonstrate the methodology.

The 10-year historical accident data analysis indicates that snowy and icy road surfaces, windy weather, and graded curves are the major critical adverse conditions for I-70. It was found that the proposed model provides a tool to assess the accident risk of a particular vehicle considering realistic driving conditions in nature, such as specific topography, wind and road surface conditions, as well as associated uncertainties. A safety index was introduced to quantify the safety margins and associated accident probabilities based on the reliability theory. After the analytical model is introduced, parametric studies of the safety index and various variables defining adverse driving conditions were conducted. GIS maps with topographic conditions embedded are generated. By displaying the data on the GIS-based map, different accident risk indices can easily be displayed and compared on the GIS map.

It is expected that this framework will help transportation authorities, truck industries, and even emergency management agencies better understand the risks, decide on the prevention policies, and educate drivers and the public, especially under inclement weather. Firstly, the trucking industry and any large-truck drivers who will drive through investigated highways can assess the risk, and interactively plan and prepare for the trip based on the forecasted weather information; secondly, the study can help transportation management agencies decide what traffic management (e.g., restrictions) enforcement should be conducted under some adverse conditions; finally, the results will provide a powerful tool for the trucking industry as well as transportation agencies to educate and train large-truck drivers about reducing accident and injury risks. It will also help the public realize the importance of safety risks exposed to large-truck drivers and other drivers sharing the same highway.

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