ACCIDENT ASSESSMENT OF VEHICLES ON LONG-SPAN BRIDGES 
AND HIGHWAYS IN STRONG WIND 

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ABSTRACT

This paper presents a framework of vehicle accident analysis model on long-span bridges in windy environments. Dynamic interaction analysis is first conducted on the vehicle-bridge system to predict the “global” bridge and vehicle dynamic responses without considering accident occurrences. The results of the global bridge-vehicle vibrations then serve as the basis for the accident analysis of the “local” vehicle vibrations. With the global vibrations as inputs of the accident model, the accident-related responses of each individual wheel are obtained and the stability condition of the vehicles are analyzed. The vehicle accidents on long-span bridges are then identified with given accident criteria.

Keywords: Vehicle accident, bridge, wind, assessment

INTRODUCTION

While little statistical information has been collected and published, threats of strong winds on the safety of vehicles have been realized and reported around the world (Baker and Reynolds, 1992). In the United States, the gust winds have also been found to be very important contributors to the accidents of vehicles especially trucks (Chen, 2004). In hurricane haunted areas, strong winds can be expected in windy season. In addition to the loss of each individual accident, the more serious issue in hurricane-prone area is that accidents constantly happening on the highways will greatly delay or even obstruct the important transportation line before or upon the landfall of hurricanes. Transportations are usually very busy and more important for hurricane preparations at those moments compared with ordinary days. If accidents happen frequently when evacuations are in progress, the whole evacuation process will be significantly delayed and the safety of those people, who cannot be evacuated in time due to the transportation interruptions, will be inevitably put on stake.

All existent analysis of vehicle accidents was limited to vehicles on the road. Moreover, the vehicle was modeled with a rigid body with only two degrees of freedom and thus no dynamic

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vibration excited by road roughness and wind forces were considered. The road roughness effect, the vertical acceleration, pitching and rolling acceleration of the vehicles were assumed to be zero. Such simplifications may be reasonable for vehicles on the road. However, the dynamic interaction effects are very important for the vehicles on bridges and should be incorporated into the accident analysis. The present study aims at building a framework of general vehicle accident analysis model, which can be used for vehicles on bridges and on roads. Excitations from the road roughness and the wind loading are incorporated. After setting up some accident criteria and driving behavior model, the accident risk can be assessed with the derived accident-related responses. To present the methodology, a truck model and a prototype bridge are chosen as the example of applications.

DYNAMIC INTERACTION OF NON-ARTICULATED VEHICLES ON BRIDGES

In the present study, a 2-axle four-wheel vehicle is modeled as a combination of several rigid bodies connected by several axle mass blocks with springs and damping devices. The suspension system and the elasticity of tires are modeled with springs. The energy dissipation capacities of the suspension as well as the tires are modeled as damping devices with viscous damping assumed. The mass of the suspension system and the tires are assumed to concentrate on idealized mass blocks on each side of the vehicle and no mass in the spring and damping devices exists (Fig. 1).

Assuming all displacements remain small, virtual works generated by the inertial forces, damping forces, and elastic forces acting on each vehicle on the bridge at a given time can be obtained. Assuming there are totally \( n_v \) vehicles running on the bridge, and the initial conditions are the equilibrium conditions of the bridge under the self-weight of the bridge only without vehicles on it. The coupled equations can be finally built from the principle of virtual work as

\[
\begin{bmatrix}
M_v & 0 \\
0 & M_b
\end{bmatrix}
\begin{bmatrix}
\dot{\gamma}_v \\
\dot{\gamma}_b
\end{bmatrix}
+ \begin{bmatrix}
C_v & C_{vb} \\
C_{bv} & C_b + C_{vb}
\end{bmatrix}
\begin{bmatrix}
\ddot{\gamma}_v \\
\ddot{\gamma}_b
\end{bmatrix}
+ \begin{bmatrix}
K_v & K_{vb} \\
K_{bv} & K_b + K_{vb}
\end{bmatrix}
\begin{bmatrix}
\dot{\gamma}_v \\
\dot{\gamma}_b
\end{bmatrix}
= \begin{bmatrix}
\{F\}_v^s + \{F\}_v^w \\
\{F\}_v^b + \{F\}_v^v + \{F\}_v^G
\end{bmatrix}
\]

(1)

where subscripts “\( b \)” and “\( v \)” represent for the bridge and vehicle, respectively; \( \gamma_v \) and \( \gamma_b \) are the displacement vectors of the vehicles and the bridge, respectively; superscripts of “\( s \)” and “\( v \)” in the stiffness and damping terms for the bridge refer to the terms of bridge structure itself and those contributed by the vehicles, respectively; subscripts “\( bv \)” and “\( vb \)” refer to the vehicles-bridge coupled terms; Matrices \( M, C \) and \( K \) are the mass, damping and stiffness matrices, respectively. \( F \) is the external loading terms. Subscripts “\( r \)”,” “\( w \)” and “\( G \)” for the \( F \) refer to the loadings due to the road roughness, wind forces, and the gravity of the vehicles, respectively; superscripts of “\( v \)” and “\( b \)” refer to the forces acting on the vehicles and on the bridge, respectively. Details of Eq. (1) can be found in Cai and Chen (2004) and are omitted here for the sake of brevity.

ACCIDENT ANALYSIS MODEL FOR VEHICLES ON BRIDGES

In the previous section, the dynamic interaction model of vehicle-bridge-wind system is briefly introduced. Such model is used to consider the dynamic interaction effects between vehicles and the bridge based on the detailed simulation of vertical stiffness and damping effect from the suspension system as well as from the tires. This interaction analysis model, however, is
built based on the assumption that each vehicle wheel has full point contact with the bridge surface all the time and there exists no lateral relative movement between the wheels and the bridge surface. Such model predicts the responses of the bridge in all directions and the responses of vehicles only in several directions such as vertical, rolling and pitching directions.

The dynamic responses of vehicles in the vertical, rolling, and pitching directions from global bridge-vehicle analysis will be carried into the local accident analysis. Relative lateral and yaw responses of vehicles, which are not available in the global analysis, however, will be calculated separately with the local accident model which emphasizes on simulating the lateral relative movement and friction effects. The effects from lateral vibrations of the bridge on vehicle dynamics are considered through treating the lateral acceleration of the bridge as the external base excitation source of the vehicles.

In the derivations of the previous section, a general case with multiple vehicles is considered and each individual vehicle is generalized as the \( q \)th vehicle. In the hereafter accident model derivation, only one typical vehicle is considered. For most vehicles, the driving wheels are usually the rear ones and the steering wheels are the front ones. So the traction forces \( T \) only exists in the two rear wheels and the steering angle \( \delta \) only exists for the two front wheels (Baker, 1986).

The wheel rolling resistance forces \( F_i \) (moving along the \( x \) axis direction) are related to the vertical forces as:

\[
F_i^f = n^r N_i^f \quad F_i^r = n^r N_i^r \quad (i = 1 \text{ to } 2) \tag{2a, b}
\]

where \( n^r \) is a coefficient of rolling friction (with negative value) and can be estimated as a constant or with some simple formulas at elementary level (Baker, 1986); superscripts “\( f \)” and “\( r \)” denote the front wheels and rear wheels; and \( N_i \) is the reaction forces of the \( i \)th wheel. Aligning moment arising from the tire lateral frictions is omitted here.

When the side slipping angle is small, the tire side slipping forces \( H_i \) (along the \( y \) axis direction) can be related, approximately in a linear way, to the vertical reactions as (Baker, 1991):

\[
H_i^f = m^\alpha N_i^f \quad H_i^r = m^\alpha N_i^r \quad (i = 1 \text{ to } 2) \tag{3a, b}
\]

where \( m^\alpha \) is a cornering stiffness coefficient and \( \alpha^f \) and \( \alpha^r \) are the side slipping angles for the front wheels and rear wheels, respectively.

The side slipping angles for the front wheels and rear wheels can be expressed as

\[
\alpha_i^f = \gamma - \frac{\psi L_1}{V} + \delta_i \quad \alpha_i^r = \gamma + \frac{\psi L_2}{V} \tag{4a, b}
\]

where \( \psi \) is the yaw angle of the vehicle at the center of the gravity around axis \( z \); \( \delta_i \) is the steering angle of the \( i \)th wheel (it is zero for rear wheels and the same for the two front wheels here); \( L_1 \) and \( L_2 \) are the horizontal distance between the center of gravity to the front wheels and rear wheels, respectively; \( \gamma \) is the vehicle body side slipping angle at the gravity center and defined by

\[
\gamma = -\arctan \left( \frac{v}{V} \right) \approx -\frac{v}{V} \tag{5}
\]

where \( v \) is the side slipping (lateral) velocity of the vehicle body relative to the road surface; and \( V(t) \) is the longitudinal driving speed of vehicle at time \( t \).

The force and moment equilibrium equations in three directions should be satisfied. By
denoting \( Y \) as the lateral displacement, the coupled equations of motion can be finally written in the state-form as:

\[
\begin{bmatrix}
\frac{d\{\xi\}}{dt}
\end{bmatrix} = \begin{bmatrix} A \\
B
\end{bmatrix} \begin{bmatrix} \{\xi\} \\
\{Y\}
\end{bmatrix} + \begin{bmatrix} C \\
\{C\}
\end{bmatrix}
\]

where

\[
A = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix},
B = \begin{bmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & \beta_5 & \beta_6 \\
0 & 0 & \beta_9 & \beta_{10}
\end{bmatrix}, 
\begin{bmatrix} \{\xi\} \\
\{Y\}
\end{bmatrix} = \begin{bmatrix}
Y \\
\psi \\
\dot{Y} \\
\dot{\psi}
\end{bmatrix}, 
\begin{bmatrix} \{C\}
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
\beta_4 + \beta_5 \delta \\
\beta_4 + \beta_5 \delta
\end{bmatrix}
\]

Details of the above matrices can be found in Chen (2004). With the assumed initial conditions about \( \xi \) and \( \delta \), Eq. (6) can be solved at time step \( t \) and the reaction forces of four wheels can also be quantified. The new steering angle in time \( t + \Delta t \) can be predicted with the driver behavior model based on the obtained response in time \( t \). Then this calculation procedure continues to time \( t + \Delta t \). Repeat such procedure and the whole time history of \( \xi \), reaction forces \( N_i \), and steering angle \( \delta \) can be derived. The vehicle accident can be identified based on suitable accident criteria.

The present driver behavior model is developed based on a simple idea that the steering angle should be adjusted to correct any lateral displacement of the front (steering) wheels. The adoption of the lateral responses of the front wheel other than that of the vehicle body (at C. G.) enables the yawing response can be taken care of as well. As mentioned earlier, each driver may react differently, and therefore, the present model is for demonstration only even though it gives very reasonable results. It is out of the scope of the current work in determining how driver behaviors in actual driving in a windy environment. The model is suggested based on Baker (1991) as:

\[
\delta = \frac{L_1 + L_2}{R} - \lambda_1 (Y + \psi L_1) - \lambda_2 (\dot{Y} + \dot{\psi} L_1)
\]

where \( R \) is the radius of turn; \( \lambda_1 \) and \( \lambda_2 \) are related to the driver behavior and assumed to be constants for the same driver.

Baker (1991) once gave some guidelines for accident identifications, which will be adopted here as follows: within some distance of the vehicle entering a sharp edged gust, the overturning accident is said to happen when one of the tire reaction forces \( N_i \) fell to zero, or side slipping accident is said to happen when the lateral response \( Y \) of the vehicle exceeds 0.5 m, or the rotation accident is said to happen if the yawing displacement \( \psi \) exceeds 0.2 radius. Such sharp-edged wind field exists when the vehicle just passes the bridge tower which used to block the wind action on the vehicle, or there is a strong gust acting on the vehicles and the bridge suddenly.

**NUMERICAL EXAMPLE**

The Yichang Suspension Bridge located in the south of China has a main span of 960 m and two side spans of 245 m each. Based on a preliminary analysis with modal coupling assessment technique and the observation of wind tunnel results, four important modes are considered in the present study. The vehicle model shown in Fig. 1 has seven degree-of-freedom, three for the rigid
body of the vehicle (vertical displacement $Z_{vr}$, pitching about the $y$ axis $\theta_{vr}$ and rolling about the $x$ axis $\phi_{vr}$) and the other four for the vertical displacements of the four wheels ($Z_{aL1}$, $Z_{aR1}$, $Z_{aL2}$, $Z_{aR2}$).

Wind force coefficients used by Baker (1986) are adopted here: The turbulent wind velocities are simulated along the bridge span with the simulation interval $\Delta = 25$ m, corresponding to the length of four elements along the main span. The total number of frequency intervals $N_f = 1024$ and the upper cutoff frequency is $2\pi$. The roughness displacement is also derived after the adoption of roughness factor of $20 \times 10^{-6}$ m$^3$/cycle for good road condition.

![Diagram showing bridge structure and vehicle](image)

**FIG. 1. Vehicle used in the example: (a) elevation view (b) cross-section view**

As discussed earlier, with the bridge-vehicle interaction model, the time history of vehicle responses can be predicted for accident analysis. Interaction analysis starts from the first vehicle enters the bridge until the first vehicle leaves the bridge. Fig. 2 shows the accelerations of vehicles in the vertical direction of the first vehicle with the same driving speed of 22 m/s versus the time under wind speed $U=30$ m/s. The small sketch of the bridge indicates the corresponding location of the first vehicle on the bridge at any given time. As will be seen later, vehicle accelerations in these directions will be used in the accident assessment.

In Fig. 2, relatively larger accelerations can be observed when the vehicle moves to the middle range of the main span with 30 m/s wind speed. Such tendency, however, is not noticeable when the wind speed is as low as 5 m/s. It is maybe because the acceleration contribution from the bridge to the vehicle is relatively small when wind speed is low. Fig. 3 gives the relative responses of the vehicle in the vertical direction. Slightly larger relative responses can be observed when vehicles move in the mid-span region of the bridge compared with vehicles moving elsewhere on the bridge when wind speed $U$ is 30 m/s (Fig. 3). Larger relative vertical response can be observed when wind speed $U$ is 30 m/s compared with that when $U=5$ m/s with the same driving speed. Relative responses, however, have no obvious increment in the middle range of the main span when wind speed $U$ is 5 m/s. Such phenomenon shows again that the interaction effect exists between vehicles and the bridge, especially when wind speed is high. To avoid losing interaction information between vehicles and the bridge in the accident assessment process, vehicle dynamic results from interaction analysis seem to be very important.
While the vehicle-bridge interaction analysis gives vehicle responses in several directions including vertical along axis z, rolling around axis x and pitching around axis y, responses in other directions, such as lateral (along axis y) and yawing (around axis z), are to be identified separately. These response are called “accident-related response” since they are critical to the assessment of accidents. The proposed model is first validated with a comparison with the results by Baker (1986) without considering driver behaviors of vehicles on the road. Vehicles may have different performance under higher wind speed. Fig. 4 shows the accident-related responses (side slipping and lateral) and the steering angle versus the travel distance when wind speed is 35 m/s (78 mph) and driving speed is 15 m/s (34 mph). The reaction force ratios are shown in Fig. 5 for the four wheels. It is found that the bolded curve (windward rear wheel) has turned to be negative in some cases, which suggests the possibilities of overturning accidents. It can also be found that the windward wheels all lose some reaction forces compared with still vehicle situation and the windward rear wheel is most likely to lose contact with the road surface.

**FIG. 2.** Vehicle accelerations when wind speed U=30 m/s and V=22 m/s

**FIG. 3.** Vehicle relative displacements when wind speed U=30 m/s and V=22 m/s
For vehicles running on the bridge with wind, it is desirable to know the highest allowable driving speed under any particular wind speed to avoid risks of accidents. Such critical driving speed is called “accident driving speed” in the present study. The three types of typical accidents (overturning accident, rotational accident, and side slipping accident) may happen concurrently or sequentially. The first occurrence is the critical one and the corresponding driving speed is the accident driving speed. As shown in Fig. 6, the accident driving speed generally decreases with the increase of wind speed. Accident analysis is also conducted for the same truck on the road, and the results are also plotted in Fig. 6. It shows that vehicles on the road have higher accident driving speed, and the upper limit wind speed under which the truck cannot keep safe is the same. At this maximum wind speed (about 35 m/s), the driving speeds are approaching zero no matter on the road or on the bridge, which means the truck can not safely move on the bridge or on the road.

CONCLUDING REMARKS

In the present study, an assessment model for vehicle accidents on bridges and on roads under wind action is introduced and following conclusions can be made:

1. The proposed accident analysis model can be used to predict the accident-related response. With suggested accident criteria and driving behavior model, the accident risks can be assessed.

2. Lowering driving speed is effective to lower the accident risk only if the wind speed is not extremely high. Setting suitable driving speed limit is important to decrease the likeliness of accident occurrence.
3. When wind speed reaches high to some extent, the vehicle should not be on the bridge no matter what driving speed it has. Rational critical wind speed limit should be set to decide when to close the bridge.

4. Overturning is most likely to happen on the bridge for high-sided vehicles, like trucks and tractor-trailer. Windward rear wheel is mostly likely to initiate the accident.

![FIG. 6. Accident driving speed versus wind speed](image)

ACKNOWLEDGMENTS

This research is partially supported by the NSF Grant CMS-0301696.

REFERENCES


